Abdollah Ghasemi · Ali Abedi
Farshid Ghasemi

Propagation Engineering in Wireless Communications

Second Edition

Springer

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Abdollah Ghasemi
Tarhe Ertebatat Telecom Consultants
Tehran, Iran

Ali Abedi
University of Maine
Orono, Maine, USA

Farshid Ghasemi
Georgia Institute of Technology
Atlanta, Georgia, USA

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Introduction

To:
All scientists and experts
who work hard to promote
the living standards of the
world community.

To meet the ever-increasing telecommunications needs of the world community, it is a crucial requirement to employ radio services. Among vast and fast expansions during recent decades, the satellite services, navigational aids, remote sensing, telemetering, audio and video broadcasting, high-speed data communications, mobile radio systems, and some other special radio services may be addressed.

Radiowaves propagating between the transmitter and receiver antennas are subject to a number of phenomena which should be studied and differentiated carefully for designing a reliable radio link. Engineering of radiowave propagation as an outstanding and highly specialized issue is required for all types of radiocommunications. The pressure to provide data for more effective use of the frequency spectrum, as a natural and limited source of radio systems, requires wider improved prediction methods especially for new bands.

The subject of radiowave propagation is now too large to be treated in a single-volume book, encompassing all theoretical and practical aspects. The purpose of this book is to deal in brief with the basic principles needed for understanding of radiowave propagation for common frequency bands used in radiocommunications. It includes descriptions of new achievements and developed propagation models. The provided materials are intended to bridge the gap between theoretical calculations and approaches and applied procedures needed for radio link design in a proper manner.

The intention of the authors is to emphasize on the propagation engineering, giving sufficient fundamental information, while going on to explain the use of basic principles together with technical achievements in this field and formulation of prediction models and planning tools for radio network design. To do this, study and analysis of main propagation phenomena and mechanisms in a professional way and based on the recommendations of the International Telecommunication Union (ITU) is a fundamental requirement.

To use the book in an efficient manner, the following points should be taken into account:

1. The primary objective of the book is to introduce the most of propagation phenomena and mechanisms likely to be encountered practically and to present fundamental principles. It serves to introduce and orient the reader to those aspects of propagation that must be considered in the design and evaluation of a radio link of a given type and operating frequency.
2. The content of the book covers most topics required for academic or applied courses regarding radiowave propagation. For better understanding, the reader is required to have a good background of advanced and applied mathematics, electromagnetic theory, and principles of radio fields and waves.
3. Considerable portion of the material at hand is based on the ITU radio recommendations. Study group no. 3 of the ITU radio sector is devoted to the studies of radiowave propagation and related results presented through series P of ITU-R recommendations.
4. A great effort is made to the extent possible, to clarify obscure points and improve existing gaps between pure theoretical approaches and practical procedures. The reader must look elsewhere for more details of the theory of radiowave propagation and analysis of phenomena such as reflection, refraction, diffraction, absorption, attenuation, precipitation, focusing/defocusing, fading, scintillation, scattering, dispersion, depolarization, etc.
5. The aim throughout the book is to give the simplest and most direct account of the applied procedures. There are over 90 solved examples distributed in volume 1 to encourage students and experts to use the relevant procedures and basic principles by themselves.
6. The whole book has been organized in two volumes each containing nine chapters. The first one includes basic principles, tropospheric and ionospheric propagation, MF/HF ionospheric links, mobile networks, fixed line of sight tropospheric links, and propagation of radiowaves in the guided media. The second volume deals with propagation mechanisms related to radar, satellite, short distance, broadcasting, and trans-horizon radio links complete with two chapters dedicated to radio noises and main parameters of radio link design.
7. The structure of each chapter typically consists of an introduction, definitions, basic formulas and expressions, applied relations, calculation procedures, tables, figures, examples, summary, questions, and problems related to the chapter topic.
8. Volume 1 includes over 155 illustrations, 20 tables, 90 solved examples, 200 questions, 158 problems, acronyms, and appendices.
9. In the case of any particular requirement for a dedicated system, specific combination of chapters may be selected. As example, for terrestrial fixed radio links, Chaps. 1, 2, 3, and 7; for terrestrial mobile radio network, Chaps. 1, 2, 3,

and 6; and for satellite links, Chaps. 1, 2, 3, and 4 of volume 1 and some dedicated chapters of volume 2 should be studied.

10. There are six appendices in volume 1 providing additional information regarding logarithmic system of units, ITU-based terms and definitions, ITU-R recommendations, list of ITU-R recommendations related to propagation (P series), references, software and websites, acronyms, and book index.

I am most grateful to my main partners in the present project, Dr. A. Abedi from the University of Maine and Dr. F. Ghasemi from the Georgia Institute of Technology, for their valuable efforts and providing necessary motivation to compile this book. I would like to appreciate also the efforts of all involved parties in the project including experts; TEC Engineering Group Dr. Farnaz Ghasemi, Dr. M. Khatir, and A. Aminpour; students F. Afghah, A. Razi, K. Yasami, and N. Hariri; and typing, drafting, and publishing groups.

Tehran, Iran A. Ghasemi
2016

Contents

Chapter 1
Introduction to Radiowaves

1.1 Introduction

In 1865 James Clerk Maxwell introduced the notion of electromagnetic (EM) waves propagating with constant speed in homogenous media, based on relations between varying electric and magnetic fields. The speed of EM waves in free space corresponds to the speed of light and is equal to 3×10^8 m/s. Several years later, a German scientist named Hertz found out that radiowaves have a nature similar to EM waves but they are invisible.

Radiowaves radiating from transmitter antenna are collected by receiver antenna after propagating between antennas. They are affected by several phenomena during propagation. The imposed effects are due to transmission media as a function of radiowave characteristics such as frequency bandwidth, polarization, and type of signal.

In general, radiowaves are some type of electromagnetic waves in a specific frequency band. Although a distinctive spectrum is not determined for radiowaves, in this book, propagational phenomena are limited to frequency bands devised by International Telecommunications Union, ITU, i.e., 3 kHz to 275 GHz.

Due to the key role of radiocommunications, a lot of studies, researches, and efforts have been spared by competent experts, institutes, organizations, and administrations all over the world for radiowave propagation and using higher-frequency bands.

Major results and achievements in radiowave propagation are collected and summarized in series P of ITU-R recommendations which are revised and updated periodically. In this book, the last version of these recommendations is employed. As a fast reference, the lists of series P of ITU-R recommendations are given in the Appendix B.

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1.2 Radio Services

Radiowaves are used for transmitting various kinds of audio, video, data, control, and navigational signals. Among numerous applications are the following groups:

- Aeronautical, land, and maritime mobile services
- Search and rescue and navigational aids
- Different types of satellite services
- Fixed services of low, medium, and high capacity
- Audio and video broadcasting
- Telemetry, SCADA, and remote sensing
- Aeronautical, land, and maritime traffic control systems
- Radio special services for industrial, scientific, research, medical, and social applications

Radio services, based on the ITU classification for frequency allocation included in the Article 5, are as follow:

1. Aeronautical mobile service
2. Aeronautical radio navigation
3. Aeronautical radio navigation satellite
4. Amateur satellite service
5. Amateur service
6. Broadcasting satellite service
7. Broadcasting service
8. Downlink service
9. Earth exploration satellite service
10. Fixed satellite service
11. Fixed service
12. Inter-satellite service
13. Land mobile service
14. Maritime mobile service
15. Maritime radio navigation
16. Meteorological aids service
17. Meteorological satellite service
18. Mobile except aeronautical service
19. Mobile satellite service
20. Mobile service
21. Radio astronomy
22. Radio determination satellite
23. Radio location
24. Radio navigation
25. Radio navigation satellite
26. Secondary (non-satellite) service
27. Secondary (satellite) service
28. Space operation service

29. Space research service
30. Standard frequency and time signal
31. Standard frequency and time signal satellite
32. Uplink service

1.3 International Codes and Standards

1.3.1 Objectives

In radiocommunications, field, codes, and standards have an outstanding position due to a number of reasons including, but not limited to, the following:

- Ever-increasing demand for a variety of services
- Growing requirements for more traffic and higher capacities
- Desired signal when radiated from transmitting antenna is beyond control and may act as an interfering source for a number of receivers except desired one(s).
- There are two parties for each radio link, i.e., transmitter and receiver. For a perfect and proper operation, their specifications should be standard and compatible; otherwise, they cannot work satisfactorily.
- In fact, standards are minimum technical requirements which shall be observed by telecommunications industries and service providers.
- Better standards result in better service quality.

1.3.2 Class of Codes and Standards

As depicted in Fig. 1.1, levels of governing codes and standards in telecommunications are as follows:

- International level adopted by international bodies such as ITU, ISO, IMO, ICAO, etc.
- Regional level adopted by a number of countries such as European Telecommunications Standard Institute, ETSI.
- National level adopted by each country such as EIA, ANSI, DIN, JSA, etc.
- Special/local level adopted by some organizations and dedicated to special networks such as Inmarsat, Intelsat, Eutelsat, TETRA, etc.

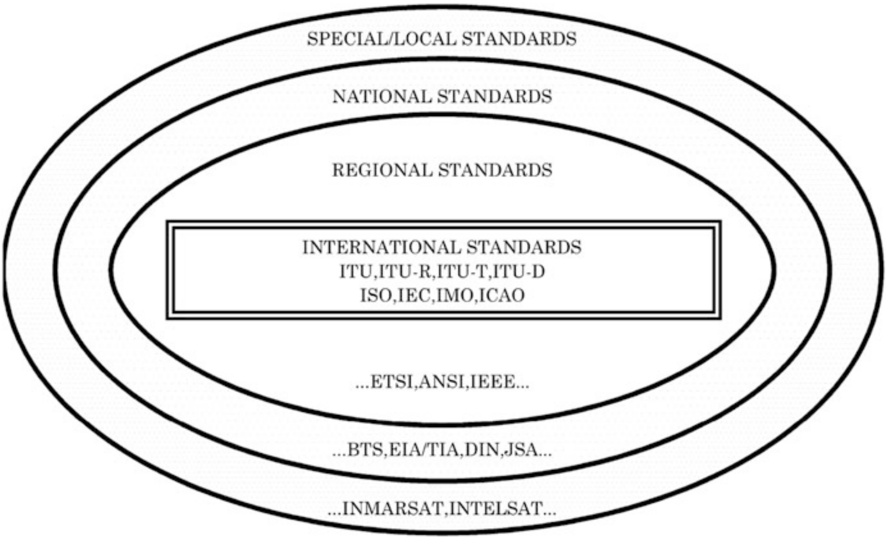


Fig. 1.1 Classification of telecommunications standards

1.3.3 Radio Regulations

ITU Radio Regulations are recognized internationally and applied by all member states/countries. The Regulations are arranged in nine chapters as follows:

Chapter I: Terminology and technical characteristics
Chapter II: Frequencies
Chapter III: Coordination, notification, and recording of frequency assignments and plan modifications
Chapter IV: Interferences
Chapter V: Administrative provisions
Chapter VI: Provisions for services and stations
Chapter VII: Distress and safety communications
Chapter VIII: Aeronautical services
Chapter IX: Maritime services

It is followed by 42 appendixes and a number of resolutions and recommendations as well. The ITU Radio Regulations usually are updated and modified accordingly through World Administrative Radio Conference (WARC) held by ITU secretariat.

1.3.4 ITU-R Recommendations

In Radio sector of ITU (known as ITU-R), a Radiocommunications Study Group has been for many years involved in introducing some technical guidelines under several recommendations on a worldwide basis. The products of ITU-R are prepared in different series named:

Series	Subject
BO	Broadcasting satellite service (sound and television)
BR	Sound and television recording
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
IS	Inter-service sharing and compatibility
M	Mobile, radiodetermination, amateur, and related satellite services
P	Radiowave propagation
RA	Radioastronomy
S	Fixed satellite service
SA	Space applications and meteorology
SF	Frequency sharing between the fixed satellite service and the fixed service
SM	Spectrum management
SNG	Satellite news gathering
TF	Time signals and frequency standards emissions
V	Vocabulary and related subjects

Series P is dedicated to the radiowaves propagation issues for which all relevant recommendations are listed in the Appendix B. These recommendations which will be referred frequently in the book are rich from technical points of view and supported by many experts in the international level.

1.4 Basic Terms and Definitions

In principal, basic terms and definitions are set by the international/professional organizations such as ITU to prevent misleading and different interpretation of technical terms. Terms and definitions used in this book are generally those specified by relevant ITU Regulations and Recommendations including ITU-R, P-310.

For a quick reference, this Recommendation is given in Appendix C. Terms and definitions correspond to the following three main sectors:

- Radiowaves
- Ground effects on radiowave propagation
- Troposphere effects on radiowave propagation

It should be noted that the terms and definitions included in Appendix C are not complete and additional items have been specified if required.

1.5 Classification of Radio Systems

There is not a general and widespread procedure for classification of radio systems. Here, two more popular ones are stated.

1.5.1 Classification Based on Frequency Bands

In this approach, radio systems are introduced with respect to their frequency band such as MF, MF/HF, HF, VHF, UHF, SHF and EHF radio systems. Other non-classic terms such as the following ones are also used occasionally:

- Shortwave (SW), medium wave (MW), and long wave (LW) in radio broadcasting
- L, C, Ku, and Ka bands in satellite communications
- S, C, and X bands in radar systems

1.5.2 Classification Based on Service Types

This approach is usually employed by ITU or end users to determine the provided services, such as:

- Aeronautical or maritime radio-navigational aids
- Audio or video broadcasting
- Fixed or mobile satellite services
- Aeronautical, land, and maritime mobile services
- Point-to-point or point-to-multipoint (P-MP) fixed radio services
- Radar systems
- Wireless communications
- Radio special services
- Radio amateur services

Each of the above services usually includes several various systems. For example, a satellite radio system may be referred to by each one of the following items:

- Fixed systems like Intelsat and Eutelsat
- Mobile systems like Inmarsat
- Meteorological satellite such as Meteosat
- Earth exploration systems
- Remote sensing and telemetry
- Audio and video broadcasting

- Navigational aids and radio determination systems
- Military systems
- National and regional satellite systems such as INSAT, Arabsat, GSAT, etc.
- VSAT systems

1.6 Radio Frequency Bands

1.6.1 Role of Frequency in Radiocommunications

Frequency, as a natural resource, has a key role in radiocommunications. In this regard, some of the major facts to clarify its crucial role in radio networks are:

- Most radiowave propagation phenomena depend on the frequency in linear or nonlinear forms.
- Dependence of technical characteristics of radio equipment and their applications and service quality on operating frequency.
- Applications of some frequency bands are exclusively allocated to the specific services.
- Limitation of frequency resources
- Ever-increasing radiocommunications requirements.

Because of new services and exploiting advanced technologies, demand for more frequency bands is increasing. To meet the new requirements, R & D centers and professional institutes at national and international levels have conducted extensive studies and investigation which among them are:

- Employing new technologies to improve frequency utilization efficiency such as higher digital modulation levels, TDMA, CDMA, and compression techniques.
- Using other transmission media such as cable TV, SDH over fiber optics cable, WDM, and DWDM
- Manufacturing RF components in higher-frequency bands
- Using network and bandwidth management systems
- Using Automatic Transmitter Power Control (ATPC) and frequency reuse techniques

1.6.2 Classification of Frequency Bands

Major frequency bands based on ITU Regulations are listed in Table 1.1. Lower and upper extremes of the ITU classic frequency bands are defined by the relation given below:

$$F/B = 3 \times 10^{n} \text{ to } 3 \times 10^{n-1} \qquad 4 \leq n \leq 11 \tag{1.1}$$

Table 1.1 ITU classic frequency bands

Wavelength, metric equivalent	Frequency range	Designation	Band number
Myriametric waves	3–30 kHz	VLF	4
Kilometric waves	30–300 kHz	LF	5
Hectometric waves	300–3000 kHz	MF	6
Decametric waves	3–30 MHz	HF	7
Metric waves	30–300 MHz	VHF	8
Decimetric waves	300–3000 MHz	UHF	9
Centimetric waves	3–30 GHz	SHF	10
Millimetric waves	30–300 GHz	EHF	11
Decimillimetric waves	300–3000 GHz	–	–
Micrometric waves	>300 THz	–	–

Table 1.2 Initial applied frequency bands

Frequency range (GHz)	Band designation
0.225–0.390	P-band
0.390–1.550	L-band
1.550–3.900	S-Band
3.900–6.200	C-band
6.200–10.900	X-band
10.900–36.00	K-band
36.000–46.000	Q-band
46.000–56.000	V-band
56.000–100.000	W-band

F/B is frequency band in Hertz and n is relevant band number as per Table 1.1.

As indicated in Tables 1.2 and 1.3, there are other classifications known as initial and new models, respectively. These frequency bands are usually employed by radio manufacturers and users, for example, L-band in maritime satellite system, C-band in satellite networks, and C and S bands in radar technology.

1.7 Application of Frequency Bands

Application of frequency bands is controlled by technical requirements and regulatory considerations but sometimes they are not matched very well. It should be noted that regulatory constraints are crucial and shall be observed by relevant manufacturers, operators, and administrations. Although structure of the book is performed according to the frequency bands but in the following sections brief descriptions are given for typical applications of each classic band.

Table 1.3 New applied frequency bands

Frequency range (GHz)	Band designation
0.100–0.250	A-Band
0.250–0.500	B-band
0.500–1.000	C-band
1.000–2.000	D-band
2.000–3.000	E-band
3.000–4.000	F-band
4.000–6.000	G-band
6.000–8.000	H-band
8.000–10.000	I-band
10.000–20.000	J-band
20.000–40.000	K-band
60.000–80.000	L-band
80.000–100.000	M-band

1.7.1 ELF, ULF, and VLF Bands

- Very limited use, because of very big antennas and poor propagation characteristics
- Low bandwidth resulting in very low data rates
- Submarine telegraphy communications
- High atmospheric noise

1.7.2 LF Band (30–300 kHz)

- Ground waves in short distance communications
- Ground-based waveguide for long-distance communications
- Broadcasting and time signals
- Radio-navigational aids
- High atmospheric noise and limited bandwidth

1.7.3 MF Band (300–3000 kHz)

- Ground waves in short distance communications
- Ground-based or ionospheric hops in long-distance communications specially in night periods
- Radio broadcasting service in LW (long wave) band
- Maritime mobile and radio navigation services

1.7.4 HF Band (3–30 MHz)

- Ionospheric long haul hops
- Radio broadcasting service in SW (shortwave) band
- Aeronautical and maritime mobile communications

1.7.5 VHF Band (30–300 MHz)

- Line-of-sight (LOS) communications using reflective waves
- Short/medium distance communications using small antennas
- Long-distance receiving due to duct effects
- Audio and video broadcasting
- Aeronautical and maritime radiocommunications
- Over-horizon radiocommunication by troposcatters
- Radar and radio navigation services
- Analog cordless telephone and radio paging services
- LEO satellite systems

1.7.6 UHF Band (300–3000 MHz)

- Line-of-sight (LOS) radiocommunications
- TV broadcasting
- Cellular mobile radio services for public applications
- Private mobile radio networks
- Mobile satellite, GPS, and astronomy communications
- Cordless telephone and radio paging services
- P-P, P-MP, and fixed radio access services
- Over-horizon radiocommunications by troposcatters
- Radar and radio navigation services
- Wireless local loops (WLL) and WiMAX

1.7.7 SHF Band (3–30 GHz)

- Line-of-sight (LOS) microwave systems
- Fixed and mobile satellite networks
- Radar systems and military applications
- Over-horizon radiocommunication by troposcatters
- P-P, P-MP, and fixed radio access systems

- TV satellite broadcasting
- Remote sensing from satellites

1.7.8 EHF Band (30–300 GHz)

- High-frequency microwave systems
- Broadband fixed wireless access
- Future satellite and high-altitude platforms applications

1.7.9 Micrometric and Nanometric Bands

- Space radiocommunications
- Special satellite communications
- Laser and infrared radiocommunications
- Fiber optics cable networks

1.8 Frequency Allocation

1.8.1 Introduction

Radio frequency band, as a limited natural radio resource, shall be allocated to a variety of radio services stated in Sect. 1.2. Frequency band allocation shall be studied carefully and be coordinated on worldwide basis. Major significant considerations are:

- Geographical distribution
- Types of radio services
- Volume of communications traffic
- Technical limitations
- Radiowaves propagation characteristics
- Edge of radio technologies

ITU has spent a lot of efforts to prepare the Article 5 of radio regulation for frequency allocation ranging from 9 kHz to 275 GHz bands. The table and related footnotes have been revised several times and also will be modified in future taking into account technical achievements and new arising services.

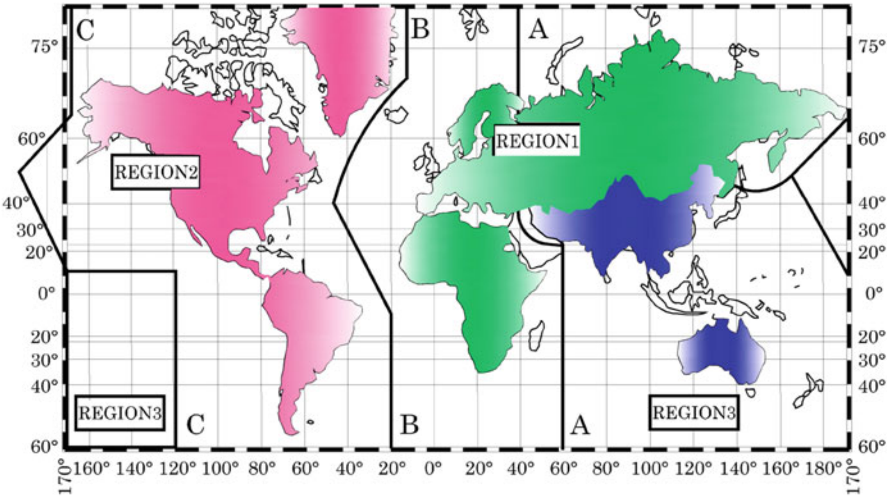


Fig. 1.2 ITU regions chart for frequency allocation

1.8.2 Frequency Registration

Frequency registration shall be performed by every competent authorized administration for all assigned frequencies within each country. This shall be done for protection of the assigned frequencies from harmful interference.

Also, on worldwide basis, main aspects of assigned frequencies in the selected services shall be registered in the International Frequency Registration Board (IFRB) for global coordination. For more details of procedures and regulations, reference is made to the ITU website and publications.

1.8.3 ITU Regions for Frequency Allocation

A chart has been prepared by ITU for Earth regional classification. As shown in Fig. 1.2, the whole earth is divided by 3 lines A, B, and C into three regions named region 1, 2, and 3. Each country is located in one of the regions. For more details, see the Article 5 and Appendix 24 of the Radio Regulations.

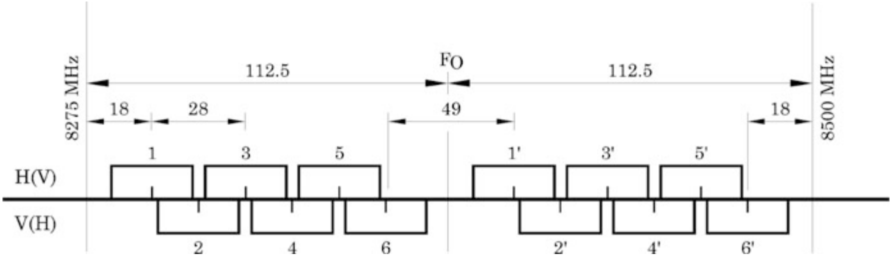


Fig. 1.3 RF channel arrangement for 8 GHz band (6-channel, 14 MHz separation)

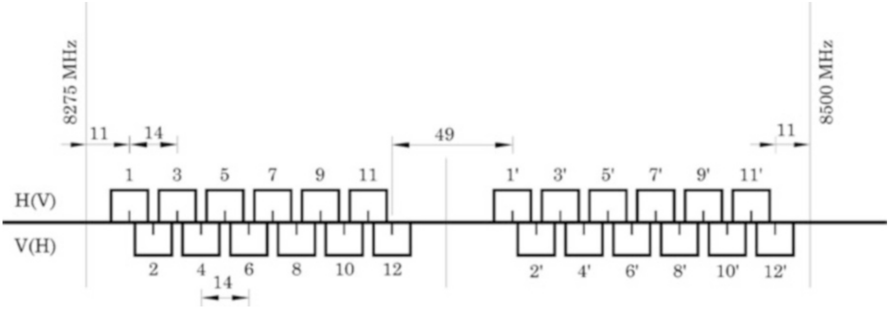


Fig. 1.4 RF channel arrangement for 8 GHz band (12-channel, 7 MHz separation)

1.8.4 Frequency Assignment

In addition to the Article 5 for frequency bands allocation, ITU and ITU-R have prepared several tables and arrangements through a number of appendices and recommendations as follow:

- Appendices 16, 17, 18, 25, 26, and 27 of Radio Regulations including Tables of RF carrier frequencies for maritime and aeronautical mobile radio services in MF, HF, and VHF bands.
- RF Channel Arrangements for satellite services included in Appendixes 30, 30A, and 30B of the Radio Regulations.

Example 1.1. Two types of RF channel arrangement extracted from ITU-R, F.386, in 8 GHz frequency band are given below (Fig. 1.3):

1. 6-RF channels with 14 MHz separation and following criteria:

$$f_n = f_0 - 108.5 + 14\,n, \quad f_0 = 8387.5\,\text{MHz}$$
$$f'_n = f_0 + 10.5 + 14\,n, \quad n = 1, 2, \ldots, 6$$

Using the above formula, carrier frequencies of TX and RX channels are (Fig. 1.4):

$$\left|\begin{matrix} f_1 = 8293 \\ f'_1 = 8412 \end{matrix}\right. \qquad \left|\begin{matrix} f_2 = 8307 \\ f'_2 = 8426 \end{matrix}\right. \qquad \left|\begin{matrix} f_3 = 8321 \\ f'_3 = 8440 \end{matrix}\right.$$

$$\left|\begin{matrix} f_4 = 8335 \\ f'_4 = 8454 \end{matrix}\right. \qquad \left|\begin{matrix} f_5 = 8349 \\ f'_5 = 8468 \end{matrix}\right. \qquad \left|\begin{matrix} f_6 = 8363 \\ f'_6 = 8482 \end{matrix}\right.$$

2. 12-RF channels with 7 MHz separation and the following criteria:

$$f_n = f_0 - 108.5 + 7n, \quad f_0 = 8387.5\,\text{MHz}$$

$$f'_n = f_0 + 17.5 + 7n, \quad n = 1, 2, \ldots, 12$$

Using the above formula, carrier frequencies of TX and RX channels are:

$$\left|\begin{matrix} f_1 = 8286 \\ f'_1 = 8412 \end{matrix}\right. \qquad \left|\begin{matrix} f_2 = 8293 \\ f'_2 = 8419 \end{matrix}\right. \quad \cdots \quad \left|\begin{matrix} f_{12} = 8363 \\ f'_{12} = 8489 \end{matrix}\right.$$

■

Example 1.2. A GEO satellite is equipped with totally 9 transponders including 3 units with 72 MHz bandwidth and 6 units with 36 MHz bandwidth. In case of using satellite C-band, i.e., 3700–4200 MHz for downlinks and 5925–6425 MHz for uplinks, answer the following questions:

1. How much is available bandwidth and is it possible to design a suitable RF channel arrangement by one-type polarization?
2. Is it possible to increase frequency utilization efficiency?

Solution. Total available bandwidth is 500 MHz which is sufficient for required RF channel arrangement with one-type polarization say right-hand circular (RHC) as shown in Fig. 1.5.

Also frequency utilization efficiency may be increased by using the same RF channel arrangement but with another polarization such as left-hand circular (LHC).

■

1.9 Atmosphere Layers

Earth atmosphere consists of different gases, vapors, meteors, hydrometeors, and dust particles. Some items are permanent and fixed but some others are temporary and varying. The permanent components of the atmosphere under influence of sun and other stars make different layers with particular features. Major Earth atmosphere layers as depicted on Fig. 1.6 are:

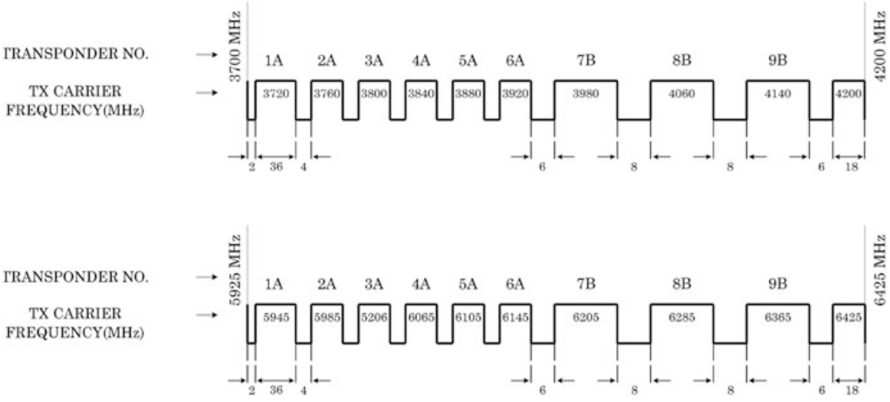


Fig. 1.5 Satellite C-band RF channel arrangement

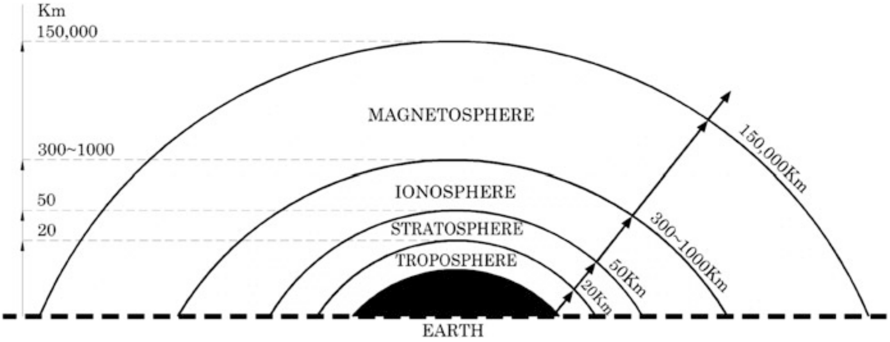


Fig. 1.6 Earth atmosphere layers

- Troposphere
- Stratosphere
- Ionosphere
- Magnetosphere

Ionosphere has three distinct sub-layers called D, E, and F, which the last one is divided to F_1 and F_2 sub-layer in day period.

Height and depth of each main layer is shown in Fig. 1.6; however, it should be noted that different values are given in references.

1.9.1 Troposphere Layer

This layer extends from Earth surface up to approximately 20 km above it and includes climatic phenomena such as rain, snow, cloud, fog, wind, and storm. Radiowaves passing through the Earth atmosphere are subject to the following major effects:

- Absorption and attenuation
- Reflection
- Refraction
- Changes of polarization
- Scattering and diffusion

One of main features of wet particles like rain, snow, etc. is their frequency-dependent attenuation. The index of relative permittivity can be introduced as follows:

$$\epsilon_r = \epsilon_r' - j\epsilon_r'' \tag{1.2}$$

ϵ_r' is real part of relative permittivity index and causes reflection and scattering of radiowaves, while ϵ_r'' is its imaginary part which introduces absorption of radiowave power and finally imposes attenuation on it.

1.9.2 Stratosphere Layer

This layer is above troposphere and extends up to approximately 50 km above mean sea level (AMSL). Main features of this layer are:

- Contains a big portion of atmospheric gases
- Low temperature variations per height

1.9.3 Ionosphere Layer

This layer is located above stratosphere and extends up to approximately 300 km AMSL (this value is specified up to 1000 km in some references). Ionosphere has great impact on radiowave propagation and consists of three sub-layers named D, E, and F with the following main characteristics:

- ***D Sub-layer***
    1. Its height reaches to 70 km above mean sea level during day time
    2. Electron content and density is directly related to the sun activities
    3. Its impact on radiowave propagation during day time is more effective than night period with a maximum at noon and minimum in sunset
    4. Its impact during summer is more significant than winter
    5. Power absorption of D sub-layer is most significant in HF low frequencies
- ***E Sub-layer***
    1. E sub-layer is located above D sub-layer with altitude up to 100 km/AMSL
    2. It is the atmosphere lowest layer able to refract/reflect radiowaves.

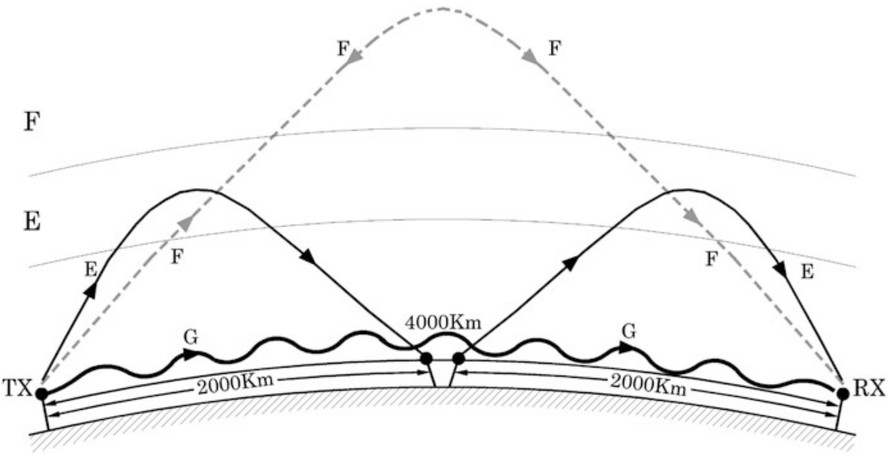


Fig. 1.7 Single hops of E and F layers

3. Its impact on radiowave propagation during day time is more than night period with a maximum at noon and a minimum in sunset.
4. Its impact during summer is greater than winter
5. Considering the refractivity nature of radiowaves, it can cover communications some 2000 km in MF/HF band (see Fig. 1.7).

- ***F Sub-layer***

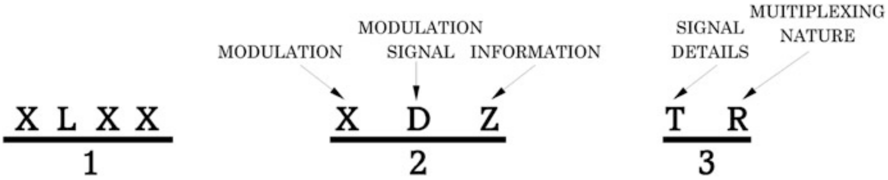
1. F sub-layer is located above E sub-layer and extends up to 300–1000 km above mean sea level
2. It provides long-distance radiocommunications up to 4000 km in HF band at night time by single radio hop (see Fig. 1.7)
3. During day time, it is divided into F_1 and F_2 layers and merging into one layer during night time.
4. F_1 acts similar to E sub-layer
5. F_2 has the greatest density of atmospheric ionization
6. F_2 is able to provide communications up to 4000 km with single radio hop

1.9.4 Magnetosphere Layer

This layer is above ionosphere and extends up to 150,000 km above Earth surface acting as an antimagnetic protective layer for Earth.

1.10 Designation of Emissions

In accordance with the ITU Radio Regulations, emissions shall be classified and symbolized according to their basic characteristics. Any full designation consists of nine symbols in the following general form:



As indicated, each designation consists of three distinct parts:

1. Necessary bandwidth including four characters for which L shall be selected one of H, K, M, and G letters denoting hertz, kilohertz, megahertz, and gigahertz, respectively. As an example 16 M3 means that necessary bandwidth is 16.3 MHz.
2. Basic characteristics including three characters Y, D, and Z

   Y: Type of modulation of the main carrier
   D: Nature of signal(s) modulating the main carrier
   Z: Type of information to be transmitted

   For details of Y, D, and Z, reference is made to the Appendix 4, extracted from subsection IIA of the ITU AP-1 (Radio Regulations 2004)
3. Optional characteristics including two characters T and R:

   T: Details of signal(s)
   R: Nature of multiplexing

   For details of T and R, reference is made to Appendix 4, extracted from subsection IIB of the ITU AP-1 (Radio Regulations, 2004)

Example 1.3. Explain characteristics of an emission in maritime mobile radio service designated by 16K0F3EJN

16K0: Signal bandwidth is 16 kHz
F: Main carrier modulation is FM
3: Modulation signal is single analog channel type
E: Information is telephony type
J: Signal quality is commercial
N: There is no multiplexing

1.11 Summary

The following issues related to radiowave propagation were explained as an introduction to the succeeding chapters:

- Telecommunications services available by radio networks for different applications in allocated frequency bands
- ITU-based chart for frequency allocation from 9 kHz to 275 GHz.
- Local, national, regional, and international category of telecommunications codes and standards.
- ITU radio regulations and ITU-R recommendations introduced and some references presented as supplementary details.
- Major applications of each frequency band listed.
- As a reference two examples presented for frequency planning of terrestrial microwave networks and GEO satellite transponders.
- Internationally recognized designations for radiowave emissions.

This chapter includes ten illustrations, three examples, and three tables for more clarification and better understanding. Also, some additional issues which may be found useful and containing more details are presented in the appendices.

1.12 Exercises

Question

1. Using the ITU-R recommendation P.310 given in the Appendix C, define the following terms:
    - Isolation of cross-polarization
    - Temperature inversion in the troposphere
    - Over-horizon (trans-horizon) propagation
    - Aerosols
    - Elevated tropospheric radio duct
    - Diffuse reflection coefficient
    - Radio horizon
2. Explain main applications of radiowaves for the time being and its future prospects.
3. Determine frequency sub-bands allocated to the maritime radio navigation at region-1 based on the Article 5 of ITU radio regulations.
4. Specify different kinds of satellite services for which there is no substitute other than radio systems.
5. Describe atmosphere layers and indicate their heights and applications in radiowaves propagation.

6. Specify reasons for using different frequencies in HF radiocommunications during day time and night time.
7. Investigate appendices to the radio regulations and ITU-F recommendation and prepare a brief report containing applications and limitations of RF channel arrangements in 1–10 GHz frequency band.
8. Explain the key role of frequency spectrum in radiocommunications and reuse techniques in frequency planning.
9. Study about potential applications of THz band and indicate main aspects and limitations.
10. List five types of telecommunication services which cannot be covered by systems other than radio types.
11. Investigate ITU-based chart of regions for frequency allocation. In what region your country is located?
12. Indicate main factors affecting the frequency band selection in terrestrial fixed radio systems.
13. Specify the bandwidth of each emission designated by 100H, 2K70, 3K40, 16M3, and 17M0.
14. Explain the meaning of each symbol for emissions designated by:

    - 134HJ2BCN
    - 2K70J3EJN
    - 2K99R3ELN
    - 3M00PONAN
    - 3M70F8EJF
    - 20K9A9WWF

15. Specify modulation type and modulating signal in emissions designated by 8M00M7EJT, 300KF8EHF, and 304HFBCN.

Problems

1. A digital radio trunk network works in 450–470 MHz band, while the bandwidth of each RF channel is 25 kHz for duplex operation. 50 kHz guard bands for lower and upper extremes and 100 kHz RF channel separation are considered.

(a) Calculate the total number of available RF channels.
(b) Assuming 200 kHz spacing between adjacent channels at each station, calculate maximum assignable RF channels per each BTS.
(c) In the case of selecting six carriers at one BTS in lower part of the band, specify go and return (TX and RX) frequencies.

2. A P-MP radio network topology is depicted in Fig. 1.8. The system works at 10.5 GHz band and maximum eight pairs of frequencies may be assigned.

(a) Specify an optimized frequency plan using only one type polarization (say vertical).
(b) Find the optimized plan by using frequency reuse techniques. Assume that only adjacent stations are in line-of-sight condition and other routes are obstructed.

3. A microwave radio network as shown in Fig. 1.9 consists of four hops in the main route ABCDE and two spur links, BK, and DM. Selected frequency band is 25 GHz with the following criteria for RF channel arrangement:

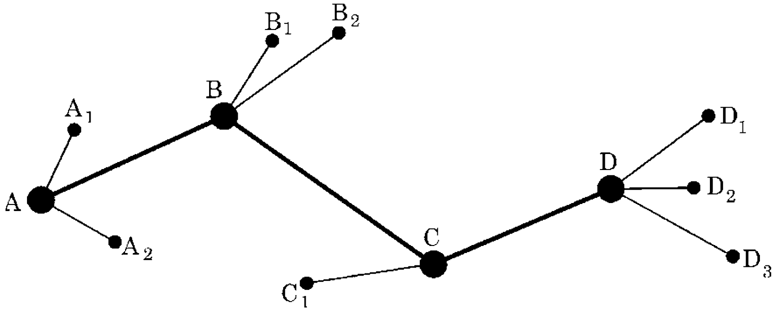


Fig. 1.8 P-MP radio network topology

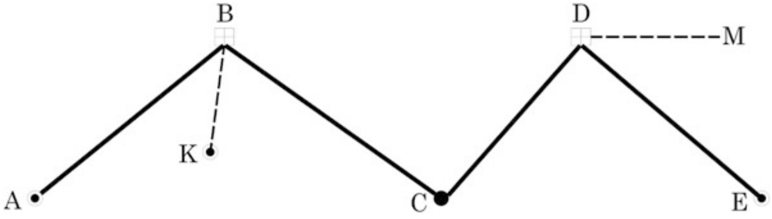


Fig. 1.9 Microwave radio network topology

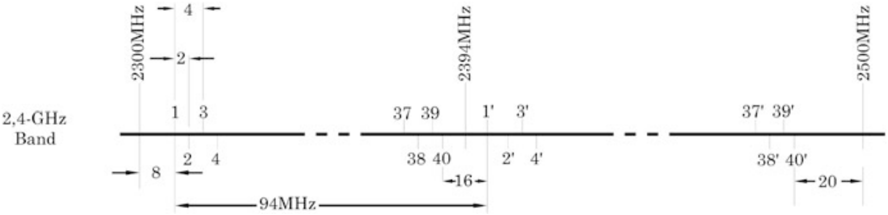


Fig. 1.10 RF channel arrangement for 2.4 GHz band

$$f_n = f_0 - 1008 + 112n, \quad n = 1, 2, \ldots, 8$$
$$f'_n = f_0 + 112n, \quad f_0 = 25{,}249\,\text{MHz}$$

(a) Specify RF channel frequency pairs.
(b) Design a frequency plan for the network by assuming (2+1) and (1+1) configurations for the main route and spur links, respectively.

4. RF channel arrangement for P-MP radio system at 2.4 GHz based on ITU-R, F.746 recommendation is shown in Fig. 1.10. Specify the following items:

- Total bandwidth
- Reference frequency (f_0)
- Number of RF channels

- Bandwidth of each RF channel
- Frequency separation between related TX and RX
- List all go and return frequencies in a table
- Find a formula to calculate the RF channel frequencies

5. A GEO satellite covering Atlantic Ocean Region (AOR) includes 12 transponders working in C-band. Bandwidth of each transponder is 36 MHz and H-type polarization is employed.

(a) Design a suitable frequency plan for the satellite.
(b) Propose the procedure to duplicate the system capacity by similar transponders.

Chapter 2
Basic Principles in Radiowave Propagation

2.1 Introduction

This chapter is dedicated to basic principles commonly used in radiowave propagation and will be frequently referred to in succeeding chapters. Due to the variety of topics to be discussed, only brief and general descriptions and formulas are given. The details can be found in more specialized references.

Among various subjects, radiowave equations and polarization, transmission media characteristics and its phenomena, K-factor and Earth equivalent radius, and free-space and basic transmission losses are included. To understand these topics, good knowledge of fields and waves theory, electromagnetic engineering, antenna theory, statistics, and applied mathematics is required. Also to get more familiar with the basic principles of radiowave propagation, some examples are presented.

To facilitate the design of radio links, supplementary issues related to the radio networks such as the following items should be considered:

- List of technical calculations
- Hypothetical reference networks
- Design criteria including availability/unavailability, reliability, quality, and performance objectives
- Unavailability budget
- Fading occurrence and fade margin
- Concept of the worst month
- Improvement and reception diversity techniques
- Radio noise

More details are outlined in a separate chapter for radio experts and designers.

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DOI 10.1007/978-3-319-32783-9_2

2.2 Transmission Media

As shown in Fig. 2.1, transmission media of radiowaves include all routes between radio transmitter and receiver consisting of one or more of the following main paths:

- Free space
- Earth atmosphere
- Ground surface and surrounding medium
- Ocean and seawater
- Inside Earth

Among the above-stated media, the first three are more important on which a lot of efforts have been spent during the recent decades at national and international levels.

2.2.1 Media Characteristics

Radiowave propagation in free space or air occurs with acceptable loss while they are attenuated rapidly in seawater or inside lands, increasing with frequency. Every medium is characterized by three parameters as mentioned below:

- Permittivity denoted by ϵ in Farad per meter (F/m)
- Permeability denoted by μ in Henry per meter (H/m)
- Conductivity denoted by σ in Siemens per meter (S/m)

Fig. 2.1 Radiowave transmission media

In free space, values of the above parameters are:

$$\sigma = 0, \quad \epsilon_0 = 8.85 \times 10^{-12}(\mathrm{F/m}), \mu_0 = 4\pi \times 10^{-7}\,(\mathrm{H/m}) \tag{2.1}$$

Conductivity of the transmission medium can be evaluated. Good conductivity is equivalent to $\frac{\sigma}{\omega\epsilon} \gg 1$, while poor conductivity is equivalent to $\frac{\sigma}{\omega\epsilon} \ll 1$.

Example 2.1. Calculate the conductivity of a piece of land specified by $\sigma = 5\,\mathrm{mS/m}$, $\mu_r = 1$ and $\epsilon_r = 12$ for radiowaves of $f_1 = 10\,\mathrm{kHz}$ and $f_2 = 10\,\mathrm{GHz}$.

Solution. For $f_1 = 10\,\mathrm{kHz}$

$$\frac{\sigma}{\omega\epsilon_r\epsilon_0} = \frac{0.005}{2\pi \times 10^4 \times 8.85 \times 10^{-12} \times 12}$$
$$= 749.3 \gg 1$$

Thus the land is of good conductivity at f_1, and for $f_2 = 10\,\mathrm{GHz}$. The conductivity index is:

$$\frac{\sigma}{\omega\epsilon_r\epsilon_0} = 7.5 \times 10^{-4} \ll 1$$

Therefore the land is a good dielectric at f_2. ■

2.2.2 Radiowave Velocity

Velocity of radiowaves is related to the medium parameters by the following formula:

$$V = \frac{1}{\sqrt{\epsilon\mu}} = \frac{1}{\sqrt{\epsilon_r\mu_r \cdot \epsilon_0 \cdot \mu_0}} \tag{2.2}$$

In the above formula, each component is defined as follows:

- V is velocity of radiowave in m/s.
- ϵ and μ are media permittivity and permeability in F/m and H/m, respectively.
- ϵ_0 and μ_0 are free-space permittivity and permeability, respectively.
- ϵ_r and μ_r are relative permittivity and permeability constants.

In free space, the velocity of radiowave is:

$$V = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 2.998 \times \mathrm{km/s} = 2.998 \times 10^8\ \mathrm{m/s} \tag{2.3}$$

This value is the same as the light velocity in free space.

We know that in linear media, the frequency does not change when the radiowave goes from one medium to another. Hence by considering the relationship among frequency, wavelength and wave velocity, i.e., $\lambda = \frac{V}{f}$, it is clear that wavelength is directly proportional to the velocity.

Example 2.2. Calculate the velocity of a radiowave propagating at 100 MHz in the following media:

1. Seawater, $\mu_r = 1$ and $\epsilon_r = 81$
2. Air with $\epsilon_r = \mu_r = 1$

Specify λ and V for $f_2 = 1\,\text{GHz}$

Solution. 1.

$$V_1 = \frac{1}{\sqrt{\mu\epsilon}} = \frac{C}{9} = 3.33 \times 10^7\,\text{m/s}$$

2.

$$V_2 = \frac{1}{\sqrt{\mu_0\epsilon_0}} = C = 3 \times 10^8\,\text{m/s}$$

Since we have assumed the medium specification to be constant with frequency, propagation velocity does not depend on frequency; thus, for both frequencies ($f_1 = 100\,\text{MHz}$ and $f_2 = 1\,\text{GHz}$), the velocity is the same.

$$f_1 = 100\,\text{MHz} \quad \Rightarrow \quad \lambda_1 = \frac{v_1}{f_1} = 0.333\,\text{m}$$

$$\lambda_2 = \frac{v_2}{f_1} = 3\,\text{m}$$

$$f_2 = 1\,\text{GHz} \quad \Rightarrow \quad \lambda_1' = \frac{v_1}{f_2} = 0.33\,\text{cm}$$

$$\lambda_2' = \frac{v_2}{f_2} = 30\,\text{cm}$$

2.2.3 Depth of Radiowave Penetration

Radiowaves passing through a lossy medium will be attenuated, and in case of significant values of attenuation rate (e^{α}), the waves will be damped rapidly. Depth of penetration is defined as a distance in the medium (like Earth) at which the wave amplitude of a radiowave incident at surface falls to 1/e (0.368) of its initial value.

In a conductor or medium with good conductivity, depth of penetration denoted by δ could be expressed by the following formula:

$$\delta = 1/\alpha = \frac{1}{\sqrt{\pi f \mu \sigma}} = \sqrt{\frac{2}{\omega \mu \sigma}} \tag{2.4}$$

In the above equation δ,f, μ, and σ represent depth of radiowave penetration, frequency, medium permeability, and medium conductivity, respectively, and all are in metric system of units.

Since δ is inversely proportional to the square root of the frequency, hence, it reduces by increasing the frequency. Evidently because of high value of δ, propagation of radiowaves is limited and rather difficult in seawater.

By simple calculations, it may be verified that for frequencies of more than 100 kHz, propagation of radiowaves in Earth land and seawater is very lossy. Even for LF and VLF bands, the wave amplitude remarkably decays along propagation, and for long distances, these waves are not of much interest.

Example 2.3. For a surface radiowave with $\bar{H} = \hat{\alpha}_y \cos(10^7 t)$, H/m propagating over land characterized by $\epsilon_r = 15$, $\mu_r = 14$ and $\sigma = 0.08$ S/m, calculate:

1. Attenuation, phase, and propagation constants
2. Depth of the land where radiowave power is reduced to half of its initial value when the wave propagates perpendicular to the land surface.

Solution. $\omega = 10^7$ rad/m

1. To qualify the land for radiowave:

$$\frac{\sigma}{\omega\epsilon} = \frac{0.08}{10^7 \times 8.85 \times 10^{-12}} = 60 \gg 1$$

The land can be assumed to be of good conductivity so the required constants are calculated as follows:

$$\alpha = \sqrt{\pi f \mu \sigma} = 0.71\,\text{Np/m}$$

$$\beta \approx \alpha \quad \Rightarrow \quad \beta = \sqrt{\pi f \mu \sigma} = 0.71\,\text{rad/m}$$

$$\gamma = \alpha + j\beta \quad \Rightarrow \quad \gamma = 0.71 + 0.71\,j\,1/\text{m}$$

2. Amplitude and power of the radiowave will decrease with rates $e^{-\alpha}$ and $e^{-2\alpha}$, respectively; thus:

$$e^{-2\alpha z} = 0.5 \quad \Rightarrow \quad z = 0.49\,\text{m}$$

■

2.3 Electromagnetic Waves

2.3.1 *Maxwell Equations*

Governing formulas for EM fields are based on Maxwell's equations with the following differential forms:

$$\bar{\nabla} \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{2.5}$$

$$\bar{\nabla} \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \tag{2.6}$$

$$\bar{\nabla} \cdot \bar{E} = \frac{\rho}{\epsilon} \tag{2.7}$$

$$\bar{\nabla} \cdot \bar{B} = 0 \tag{2.8}$$

Integral forms of the above equations over closed curve/surface are as follow:

$$\oint_c \bar{E} \cdot \bar{dl} = -\frac{d\varphi}{dt} \tag{2.9}$$

$$\oint_c \bar{H} \cdot \bar{dl} = I + \frac{\partial}{\delta t} \iint_s \bar{D} \cdot \bar{ds} \tag{2.10}$$

$$\oiint_c \bar{E} \cdot \bar{ds} = +\frac{Q}{\epsilon} \tag{2.11}$$

$$\oiint_c \bar{B} \cdot \bar{ds} = 0 \tag{2.12}$$

Also the following relations are between the main parameters:

$$\bar{B} = \mu \bar{H}, \bar{D} = \epsilon \bar{E} \tag{2.13}$$

In the above formulas, each notation stands for:

$\bar{E}$: Electric field intensity
$\bar{B}$: Magnetic flux density
$\bar{D}$: Electric flux density
$\bar{H}$: Magnetic field intensity
μ: Medium permittivity
ϵ: Medium permeability
I: Electric current intensity
Q: Electric charge

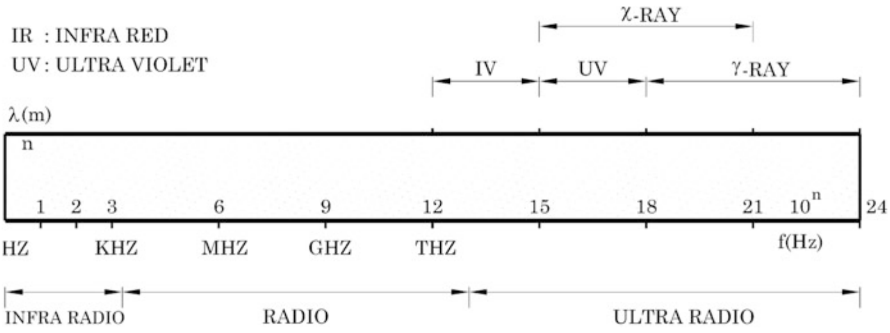

Fig. 2.2 Electromagnetic wave spectrum

2.3.2 Electromagnetic Wave Spectrum

J.C. Maxwell using mathematical relations proved that EM waves consist of time-varying electric and magnetic fields propagating in the media. In their simple form, radiowaves are time-harmonic fields in sinusoidal form with frequency f. When the medium is not dispersive, its velocity is not dependent on the frequency but is only related to the medium parameters.

EM waves spectrum includes a wide range of frequencies and as shown on Fig. 2.2 covers all infra-radio, ultra-radio, infrared, laser, visible light, ultraviolet, X-ray, and γ-ray bands.

2.4 Wave Equations and Spectrum

2.4.1 Plane Waves

Wave equations in general form, i.e., three-dimensional and in lossy media including electric and magnetic sources, are as follow:

$$\nabla^2\bar{H} - \mu\sigma\frac{\partial\bar{H}}{\partial t} - \mu\epsilon\frac{\partial^2\bar{H}}{\partial t^2} = -\bar{\nabla}\times\bar{J} \tag{2.14}$$

$$\nabla^2\bar{E} - \mu\sigma\frac{\partial\bar{E}}{\partial t} - \mu\epsilon\frac{\partial^2\bar{E}}{\partial t^2} = -\bar{\nabla}\times\bar{M} \tag{2.15}$$

In the simplest form, i.e., one-dimensional and in lossless media without any source and in time-harmonic condition, the wave equations reduce to:

$$\nabla^2 H + \omega^2\mu\epsilon H = 0 \tag{2.16}$$

$$\nabla^2 E + \omega^2\mu\epsilon E = 0 \tag{2.17}$$

The last two formulas are algebraic equations known as Helmholtz's equations consisting of three scalar equations for each field component (one per each direction). Uniform plane wave is a particular response of wave equations having similar direction, magnitude, and phase of $\bar{E}$ or $\bar{H}$ fields in planes perpendicular to the direction of wave propagation.

Phase velocity indicating radiowave velocity is:

$$V_p = \frac{dZ}{dt} = \frac{1}{\sqrt{\mu\epsilon}} \tag{2.18}$$

In free space with μ_0 and ϵ_0, radiowave velocity is equal to light velocity approximately equal to 300,000 km/s and in other media is less than 300,000 km/s due to greater values of μ_r and ϵ_r.

2.4.2 Radiowave Spectrum

Radiowave frequency bands in accordance with Article 5 of the Radio Regulations ranges from 9 kHz to 275 GHz. Also, it should be noted that in the recent years resorting to higher frequency bands has been taken into account by ITU-R through a number of study groups leading to the recommendations below:

- ITU-R, Rec. P-1621 and P-1622, using frequency band between 20 and 375 THz for the design of Earth-space systems
- ITU-R, Rec. P.1814 and P.1817, using lower portion of the optical spectrum for the design of terrestrial free-space links.

EM waves with frequencies less than 9 kHz are not employed due to the following reasons:

- Limited bandwidth resulting in low traffic capacity
- Very large antennas because of long wavelengths

Also frequency bands higher than 100 GHz are not usually employed for the time being due to the following reasons:

- High free-space loss
- High atmospheric attenuation
- Limitations in RF component manufacturing

Optical communications are available by using low visible electromagnetic waves in 850, 1310, and 1550 nm windows over fiber optic cable networks.

2.5 Media Effects on Radiowaves

Radiowaves are affected during propagation by some media phenomena which are summarized below:

- Reflection and multipath radio links
- Atmospheric refraction
- Curvature of radio path and K-factor
- Earth-based and elevated radio ducts
- Diffraction and obstruction loss
- Free-space loss
- Atmospheric attenuation due to absorptions
- Scattering of radiowaves
- Depolarization of radiowaves
- Sunspot effects
- Magnetic storms

The above phenomena are related to the troposphere layer or ionosphere layer or both. In the succeeding chapters, the mentioned effects are explained in more details.

2.6 Propagation Parameters

Main propagation parameters related to medium are:

- Characteristic impedance, η in ohm
- Attenuation constant, α in Neper/m
- Phase constant, β in rad/m
- Wave number, k in rad/m
- Propagation constant, γ in m^{-1}
- Refraction index, n

η and k normally are complex values but α and β are real quantities related to the propagation constant by $\gamma = \alpha + j\beta$. Characteristic impedance of free space is a real value:

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi = 377\,\Omega \tag{2.19}$$

Also wave number, k, for free space is a real value as follows:

$$K_0 = \omega\sqrt{\mu_0\epsilon_0} = \frac{\epsilon}{C} = \frac{2\pi}{\lambda} \tag{2.20}$$

$$\text{Light velocity} = C = 3 \times 10^8\ \text{m/s} \tag{2.21}$$

For more details of the abovementioned parameters and related formulas, reference is made to *Electromagnetic Fields and Waves* books addressed in the attachment.

2.7 Radiowave Polarization

2.7.1 Definition of Polarization

Polarization is characteristic of radiowaves which describes time-dependent variations of electric field vector $\bar{E}$ at a point in the space. To specify the polarization of a radiowave, it is not necessary to define the magnetic field vector $\bar{H}$ separately because for a plane wave in homogeneous isotropic medium $\bar{E}$ and $\bar{H}$ are perpendicular to each other and the ratio of their magnitudes is equal to intrinsic impedance of the medium. Main types of radiowaves polarization are:

1. If $\bar{E}$ is continually horizontal, its polarization is called horizontal.
2. If $\bar{E}$ is continually perpendicular to the horizontal plane, its polarization is called vertical.
3. If the projection of the head of $\bar{E}$ on a plane perpendicular to radiowave propagation direction at any point in the space follows a circle, its polarization is circular. In the case of rotation by time (for an observer looking in the direction of propagation) in clockwise (CW) direction, it is known as right-hand circular polarization, RHCP. Also, if the specified rotation is counter clockwise (CCW), it is known as left-hand circular polarization (LHCP).
4. If the projection of the head of $\bar{E}$ on a plane perpendicular to radiowave propagation direction at any point in the space follows an ellipse, its polarization is called elliptical. In the case of rotation by time (for an observer looking in the direction of propagation) in clockwise (CW) direction, it is known as right-hand elliptical polarization, RHEP. Also, if the specified rotation is CCW, it is known as left-hand elliptical polarization, LHEP.

2.8 Main Types of Radiowave Polarization

In an overall classification, radiowave polarizations are divided into linear and nonlinear types. As shown in Fig. 2.3, linear types include the following three groups:

- Horizontal
- Vertical
- Inclined

Also, nonlinear polarizations mainly consist of the following groups:

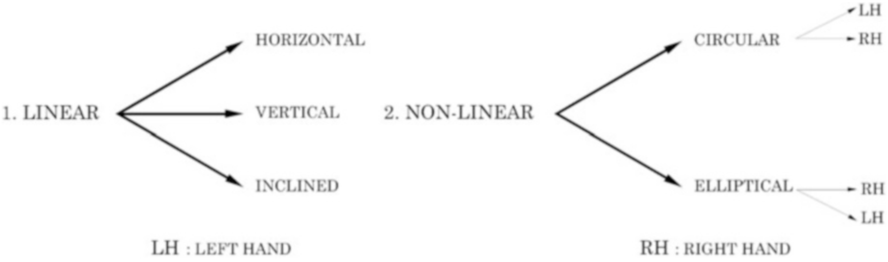

Fig. 2.3 Basic types of polarization

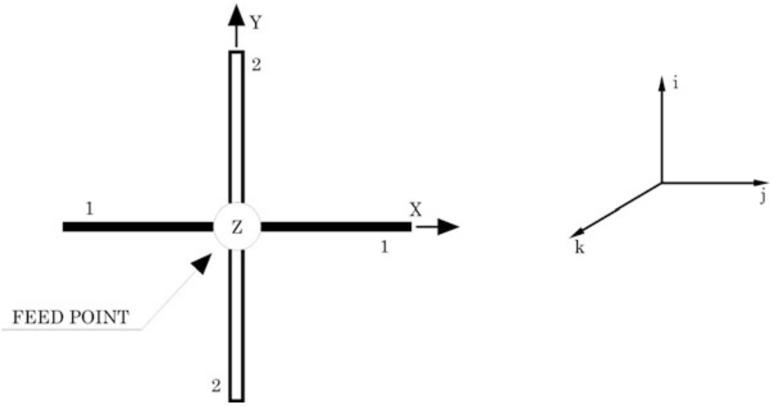

Fig. 2.4 Concept of generating polarized waves

- Right-hand circular polarization, RHCP
- Left-hand circular polarization, LHCP
- Right-hand elliptical polarization, RHEP
- Left-hand elliptical polarization, LHEP

2.8.1 Basic Polarized Radiowaves

To produce basic polarized radiowaves, a simple practical way is to employ two orthogonal dipole antennas. As shown in Fig. 2.4, antenna 1 is horizontal dipole and antenna 2 is a vertical dipole.

By proper feeding of the antennas, the following radiowaves will be generated:

$$\bar{E}_1 = E_x \times \hat{\alpha}_x = E_A \sin(\omega t - \beta z) \cdot \hat{\alpha}_x \tag{2.22}$$

$$\bar{E}_2 = E_y \times \hat{\alpha}_y = E_B \sin(\omega t - \beta z + \bar{\varphi}) \cdot \hat{\alpha}_y \tag{2.23}$$

In the plane $Z = 0$, the above relations result in:

$$Z = 0 \Rightarrow \left| \begin{array}{l} \bar{E}_1 = E_A \ \sin(\omega t) \ \cdot \ \hat{\alpha}_x \\ \bar{E}_2 = E_B \ \sin(\omega t + \phi) \ \cdot \ \hat{\alpha}_y \end{array} \right. \Rightarrow \left| \begin{array}{l} \bar{E}_X = E_A \ \sin(\omega t) \\ \bar{E}_Y = E_B \ \sin(\omega t + \phi) \end{array} \right. \tag{2.24}$$

$$\Rightarrow \ \sin\omega t = \frac{E_X}{E_A}, \quad \cos\omega t = \sqrt{1 - \left(\frac{E_X}{E_A}\right)^2} \tag{2.25}$$

$$E_Y = E_B \sin\omega t \ \cos\phi + E_B \cos\omega t \ \sin\phi \tag{2.26}$$

$$\frac{E_Y}{E_B} = \frac{E_X}{E_A}\cos\phi + \sqrt{1 - \left(\frac{E_X}{E_A}\right)^2} \ \cdot \ \sin\phi \tag{2.27}$$

By squaring the relation (2.27) and simple manipulations, we have:

$$\tfrac{E_Y^2}{E_B^2} + \tfrac{E_X^2}{E_A^2} - 2\tfrac{E_X}{E_A} \times \tfrac{E_Y}{E_B}\cos\phi = \sin^2\phi, \text{or} \tag{2.28}$$

$$E_Y^2\left(\tfrac{1}{E_B^2\sin^2\phi}\right) + E_X^2\left(\tfrac{1}{E_A^2\sin^2\phi}\right) - 2E_XE_Y\tfrac{\cos\phi}{E_A \cdot E_B\sin^2\phi} = 1 \tag{2.29}$$

The last expression is in the general form of $aE_X^2 + bE_Y^2 - cE_XE_Y = 1$ from which for various values of a, b, and c, basic polarized radiowaves may be generated as follows:

1. For horizontal polarization, only dipole 1 shall be fed, i.e., $E_A \neq 0, E_B = 0$.
2. For vertical polarization, only dipole 2 shall be fed, i.e., $E_A = 0, E_B \neq 0$.
3. For inclined linear polarization, both dipoles shall be fed in-phase with a fixed amplitude ratio, i.e., $\Phi = 0$ and $\frac{E_A}{E_B} = cte$.
4. For circular polarization, both dipoles shall be fed by equal amplitudes and ±90° phase difference.
5. If none of the above conditions are met, the polarization would be elliptical.

Example 2.4. Find polarization of a uniform plane radiowave with magnetic field: $\bar{H} = 10^{-6}(\hat{\alpha_Y} + j\hat{\alpha_Z})\cos\beta X$ A/m

Solution. Propagation of the specified radiowave is in the x-axis direction, and due to its nature, only E_y and E_z components exist. To determine the type of polarization, E-field variations versus time should be studied in a plane perpendicular to the propagation direction, say $x = 0$:

$$\bar{E} = -\eta\hat{\alpha}_x \times \bar{H} = 10^{-6} \times 120\pi[\hat{\alpha}_z - j\hat{\alpha}_y]\cos\beta x \, \text{V/m}$$

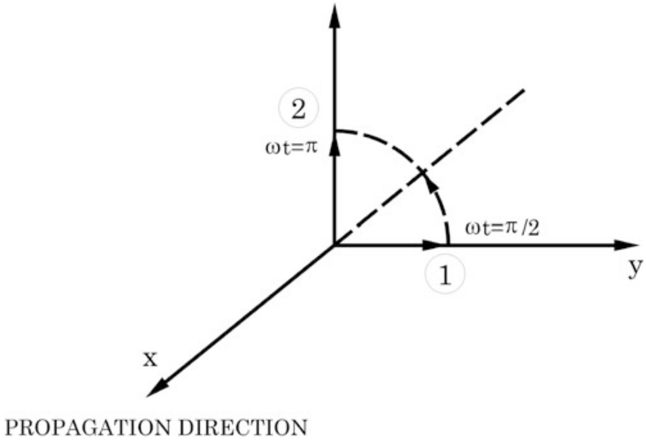

Fig. 2.5 Rotation of $\bar{E}$ with time $(\omega t = \pi/2 \; and \; \omega t = \pi)$

$\bar{E}(x,t)$ is:

$$\bar{E}(x,t) = -10^{-6} \times 120\pi [\hat{\alpha_z} \cos(\omega t - \beta x) - \hat{\alpha_y} \sin(\omega t - \beta x)]$$

$$\text{At plane } x = 0 \Rightarrow \left| \begin{array}{l} E_Z = -10^{-6} \times 120\pi \cos \omega t \\ E_Y = 10^{-6} \times 120\pi \sin \omega t \end{array} \right.$$

$$\Rightarrow \quad (E_Y)^2 + (E_Z)^2 = (10^{-6} \times 120\pi)^2 = R^2$$

It is clear that the polarization is circular. To fix rotation of $\bar{E}$ with time, its position shall be investigated by a reference observer. By using Fig. 2.5 and fixing the $\bar{E}$ positions at say $\omega t = \pi/2$ and $\omega t = \pi$, respectively, direction of radiowave rotation can be determined.

For $\omega t = \pi/2$, $\bar{E}$ position is shown by **1** and for $\omega t = \pi$ by **2**, thus the rotation of $\bar{E}$ for reference observer is clockwise and it is concluded that the radiowave polarization is RHCP. ■

Example 2.5. Determine polarization of a radiowave expressed by $\bar{E} = (A\hat{\alpha_X} + jB\hat{\alpha_Y})e^{-j\beta Z}$

Solution. Propagation is in Z-axis direction and at plane $Z = 0$; thus, $\bar{E}$ field components are:

$$\left| \begin{array}{l} E_X = A \cos \omega t \\ E_Y = B \sin \omega t \end{array} \right. \Rightarrow \left(\frac{E_X}{A}\right)^2 + \left(\frac{E_Y}{B}\right)^2 = 1$$

Polarization of the radiowave will change based on A and B conditions as follow:

$A = 0, B \neq 0$ Vertical (linear)
$A \neq 0, B = 0$ Horizontal (linear)
$A = B \neq 0$ Circular
$A \neq B \neq 0$ Elliptical

To determine the rotation of $\bar{E}$, its position should be studied at two different times, say $t = 0$ and $t = \pi/2$:

$$\left| \begin{array}{lll} \omega t = 0 & \Rightarrow & E_X = A, \;\; E_Y = 0 \\ \omega t = \pi/2 & \Rightarrow & E_X = 0, \;\; E_Y = B \end{array} \right.$$

$$\begin{array}{lll} a > 0, \;\; b > 0 & \Rightarrow & \text{CW, right hand} \\ a > 0, \;\; b < 0 & \Rightarrow & \text{CCW, left hand} \\ a < 0, \;\; b > 0 & \Rightarrow & \text{CCW, left hand} \\ a < 0, \;\; b < 0 & \Rightarrow & \text{CW, right hand} \end{array}$$

■

2.9 Radio Links

Different types of radio links may be propagating between transmitter and receiver radio units. As shown in Fig. 2.6, the main types of radio links are:

1. Ground waves commonly used for AM broadcasting, radio navigational aids, and shortwave radio systems
2. Reflective waves producing multipath links along with the main route which are common in UHF and microwave radio links including FM broadcasting in TV networks as well
3. Line-of-sight (LOS) links used in terrestrial microwave, UHF, and radar networks
4. Tropospheric links for point-to-point telecommunications by refracting/reflecting waves through troposphere layer and using over-horizon troposcatters
5. Ionospheric links employed for long-distance telecommunications using reflection from ionosphere D, E, and F layers in MF, HF, and public audio broadcasting networks
6. Satellite links for communications between satellites and ground stations with a distance ranging from several hundred up to around 40,000 km
7. Radio links for space telecommunications between ground and spacecraft stations

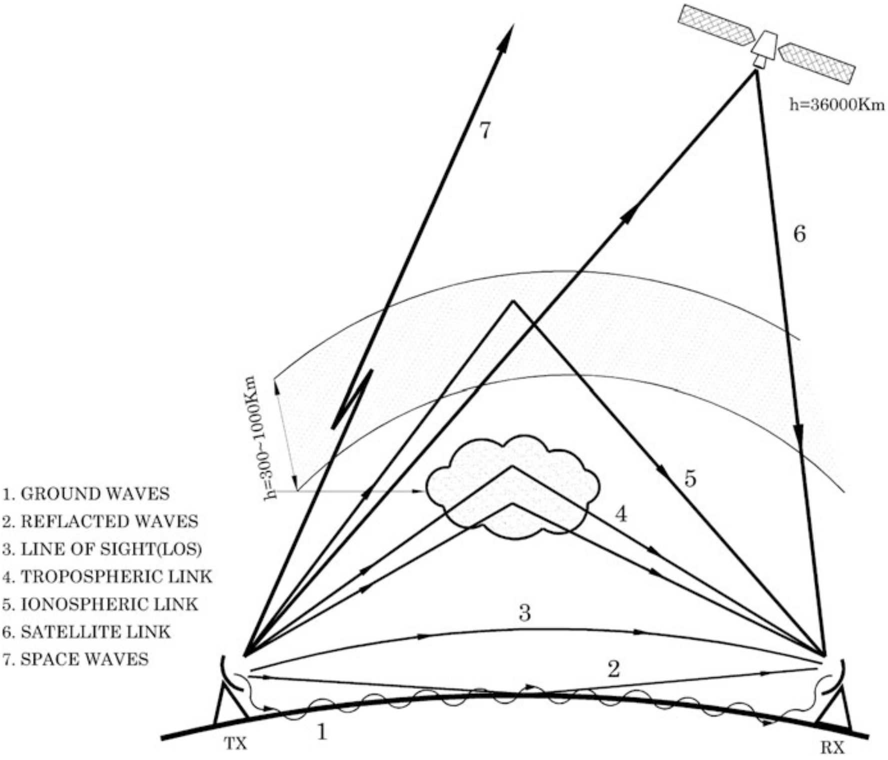

Fig. 2.6 Types of main radio links

2.10 Free-Space Loss

Free space is an ideal condition without any energy absorption or adverse propagation effects. When radiowaves are radiated in the space by an isotropic antenna, they will propagate identically in all directions.

2.10.1 Power Flux Density

Instantaneous power flux density W_i of a plane wave at any location in the space based on electromagnetic theory is:

$$W_i = |\bar{E} \times \bar{H}| = c\epsilon_0|\bar{E}|^2 = c\mu_0|\bar{H}|^2 \tag{2.30}$$

E and H denote electric and magnetic fields in V/m and A/m, respectively; W_i is maximum power flux density in $\mathrm{W/m^2}$. Applying relevant equation yields:

$$\frac{1}{c\epsilon_0} = c\mu_0 = \eta_0 = 120\pi\,\Omega \tag{2.31}$$

Mean value of W_i based on sinusoidal nature of radiowaves, denoted by W, is expressed by:

$$W = \frac{1}{2}W_i = \frac{1}{2\eta_0}|E|^2 = \frac{\eta_0}{2}|H|^2 \tag{2.32}$$

Example 2.6. At a given location, the mean value of power flux density is $100\,\mathrm{pW/m^2}$, calculate effective values of E and H.

Solution.

$$W = 100\,\mathrm{pW/m^2} \quad \Rightarrow \quad E_m = \sqrt{2\eta_0 \cdot W}$$

$$E_m = 275\,\mu\mathrm{V/m} \quad \Rightarrow \quad E_e = \frac{E_m}{\sqrt{2}} = 196\,\mu\mathrm{V/m}$$

$$H_m = \sqrt{\frac{2\times 10^{-10}}{120\pi}} = 0.728\,\mu\mathrm{A/m} \ \Rightarrow \ H_e = 0.52\,\mu\mathrm{A/m}$$

■

2.10.2 Free-Space Loss

Radiation of radio power P_t by an isotropic antenna in free space results in power flux density P_0 at a distance d:

$$P_0 = \frac{P_t}{4\pi d^2} = \frac{E_0^2}{2\eta_0} \tag{2.33}$$

In the above formula, P_t is the transmitter power in Watts, d is the distance from antenna in m, E_0 is electric field magnitude in V/m, and η_0 is free-space intrinsic impedance equal to $120\pi\,\Omega$. Applying G_t as TX antenna gain, power flux density P will be:

$$P = \frac{P_t \cdot G_t}{4\pi d^2} \tag{2.34}$$

Using a receiving antenna with effective aperture area A_e, received signal power would be:

$$P_r = P \cdot A_e \tag{2.35}$$

A_e according to the EM waves theory is:

$$A_e = \frac{G_r \cdot \lambda^2}{4\pi} \tag{2.36}$$

By manipulating the last three relations, the following formula is derived:

$$P_r = \frac{P_t \cdot G_t}{4\pi d^2} \times \frac{G_r \cdot \lambda^2}{4\pi} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi d)^2} \tag{2.37}$$

To calculate free-space loss by using the above relation and assuming $G_t = G_r = 1$:

$$L_{fb} = \text{FSL} = 10\ \log \frac{P_t}{P_r} = -10\ \log \frac{\lambda^2}{(4\pi d)^2} \tag{2.38}$$

$$\Rightarrow \quad \text{FSL} = 20\ \log \frac{4\pi d}{\lambda} \tag{2.39}$$

Considering $\lambda = c/f$, we have:

$$\text{FSL} = 20\ \log \frac{4\pi f \cdot d}{c} \tag{2.40}$$

The above formula is generic form of FSL in metric system of units. Since in actual links the frequency is in MHz or GHz and distance in km, by putting $c = 3 \times 10^8$ m/s, then FSL is specified by one of the following formulas:

$$\text{FSL[dB]} = 32.4 + 20\ \log f[\text{MHz}] + 20\ \log d[\text{km}] \tag{2.41}$$

$$\text{FSL[dB]} = 92.4 + 20\ \log f[\text{GHz}] + 20\ \log d[\text{km}] \tag{2.42}$$

Example 2.7. In a radio link of 40 km length and working at 7.5 GHz, 60 % of free-space loss is compensated by using high-gain TX and RX antennas.

1. How much is the received signal level (RSL) at the output of RX antenna with one watt TX output power and considering 15 dB additional losses?
2. Find fade margin of the link if RX threshold is to be $P_{\text{th}} = -78\,\text{dB}_m$.

Solution. 1.

$$\text{FSL} = 92.4 + 20\ \log f \cdot d = 141\,\text{dB}$$

$$P_t = 1\,\text{W} \quad \Rightarrow \quad P_t[\text{dB}_m] = 30\,\text{dB}_m$$

$$P_r = \text{RSL} = P_t[\text{dB}_m] - 0.4\ \text{FSL} - L_a$$

$$= 30 - 56.8 - 15 = -41.4\,\text{dB}_m$$

2.

$$\mathrm{FM} = P_r[\mathrm{dB}_m] - P_{\mathrm{th}}[db_m] = -41.4 + 78 = 36.6\,\mathrm{dB}$$

■

2.10.3 ITU-R Formulas

Considering that free-space propagation is a fundamental reference for engineering of radio links, ITU-R assembly recommends Rec. P.525 that the following methods be used for the calculation of attenuation in free space.

2.10.3.1 Point-to-Area Links

If there is a transmitter serving several randomly distributed receivers (broadcasting, mobile service), the field strength is calculated at a point located at some appropriate distance from the transmitter by the expression:

$$e = \frac{\sqrt{30p}}{d} \tag{2.43}$$

where:

e: r.m.s. field strength (V/m)
p: Equivalent isotropically radiated power (e.i.r.p.) of the transmitter in the direction of the point in question
d: Distance from the transmitter to the point in question (m)

Equation (2.43) is often replaced by Eq. (2.44) which uses practical units:

$$e_m[\mathrm{V/m}] = 173\frac{\sqrt{p\ [\mathrm{kW}]}}{d\ [\mathrm{km}]} \tag{2.44}$$

For antennas operating in free-space conditions, the cymomotive force as defined by ITU-R may be obtained by multiplying together e and d in Eq. (2.43). Its dimension is volts and to apply the above formulas, the following points shall be taken into account:

- If the wave is elliptically polarized and not linear, and if the electric field components along two orthogonal axes are expressed by e_x and e_y, the left-hand term of Eq. (2.43) should be replaced by $\sqrt{e_x^2 + e_y^2}$ or it may be simplified only if the axial ratio is known. The term e should be replaced by $e\sqrt{2}$ in the case of circular polarization.

- In the case of antennas located at ground level and operating on relatively low frequencies with vertical polarization, radiation is generally considered only in the upper half-space. This should be taken into account in determining the e.i.r.p. (see Recommendation ITU-R PN.368).

2.10.3.2 Point-to-Point Links

With a point-to-point link, it is preferable to calculate the free-space attenuation between isotropic antennas, also known as the free-space basic transmission loss (symbols: L_{bf} or A_0), as follows:

$$L_{bf} = 20 \log \left(\frac{4\pi}{\lambda} \right) \tag{2.45}$$

where:

L_{bf}: Free-space basic transmission loss (dB)
d: Distance
λ: Wavelength, and

d and λ are expressed in the same unit.

Equation (2.45) can also be written using the frequency instead of the wavelength:

$$L_{bf} = 32.4 + 20 \log f + 20 \log\ d \tag{2.46}$$

where:

f: Frequency (MHz)
d: Distance (km)

2.10.3.3 Radar Links

Radar systems represent a special case because the signal is subjected to a loss while propagating both from the transmitter to the target and from the target to the receiver. For radars using a common antenna for both transmitter and receiver, a radar free-space basic transmission loss, L_{br}, can be written as follows:

$$L_{br}[\mathrm{dB}] = 103.4 + 20 \log f + 40 \log\ d - 10 \log\ \sigma \tag{2.47}$$

where:

σ: Radar target cross-section (m^2)
d: Distance from the radar to the target (km)
f: Frequency of the system (MHz)

The radar target cross-section of an object is the ratio of the total isotropically equivalent scattered power to the incident power density.

2.10.3.4 Power Flux Density

There are also relations between the characteristics of a plane wave (or a wave which can be treated as a plane wave) at a point:

$$S = \frac{e^2}{120\,\pi} = \frac{4\pi p_r}{\lambda^2} \tag{2.48}$$

where:

S: Power flux density (W/m^2)
e: r.m.s. field strength (V/m)
p_r: Power (W) available from an isotropic antenna located at this point
λ: Wavelength (m)

2.10.3.5 Conversion Relations

On the basis of free-space propagation, the following conversion formulas may be used. Field strength for a given isotropically transmitted power:

$$E = P_t - 20\log\, d + 74.8 \tag{2.49}$$

Isotropically received power for a given field strength:

$$P_r = E - 20\log f - 167.2 \tag{2.50}$$

Free-space basic transmission loss for a given isotropically transmitted power and field strength:

$$L_{bf} = P_t - E + 20\log f + 167.2 \tag{2.51}$$

Power flux density for a given field strength:

$$S = E - 145.8 \tag{2.52}$$

where:

P_t: Isotropically transmitted power (dB(W))
P_r: Isotropically received power (dB(W))
E: Electric field strength (dB(μV/m))
f: Frequency (GHz)

d: Radio path length (km)
L_{bf}: Free-space basic transmission loss (dB)
S: Power flux density (dB(W/m^2))

Note that Eqs. (2.49) and (2.51) can be used to derive Eq. (2.46).

2.11 Equivalent Radiated Power

2.11.1 Antenna Gain

Antenna gain is defined as "the ratio of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce the same field strength or the same power flux density at the same distance and in the desired direction."

Usually, antenna gain is expressed in decibels and refers to the direction of maximum radiation. The amount of gain is proportional to its dimension compared to the RF wavelength (λ) and design efficiency. In general, antennas being used in higher frequency bands such as SHF and EHF are high gain, while antennas in LF/MF/HF frequency bands are normally medium/low gain types.

A variety of antennas are employed in radio networks among which the following types are more common:

- T-type, inverted-L, conical, biconical, rhombic, and log-periodic used in LF, MF, and HF radiocommunications and AM broadcasting.
- Whip, collinear, Yagi, and corner reflector used in VHF/UHF radio systems and FM and TV broadcasting
- Horn and panel antennas in UHF/SHF frequency bands used in line-of-sight radio links.
- Directional antennas of high gain such as parabolic or Cassegrain used in microwave and satellite telecommunications.
- Special antennas for specific applications such as radio navigations, GPS, etc.

Antenna gain, depending on the selected reference antenna, may be expressed in different ways as follows:

1. When reference antenna is an isotropic antenna isolated in free space, then gain is denoted by G_i and known as isotropic or absolute gain.
2. When reference antenna is a half wave dipole isolated in free space whose equatorial plane contains the given direction then the gain is denoted by G_d and known as dipole-related gain. Between dipole and isotropic gains for a given antenna, the following relation exists:

$$G[\mathrm{dB}_i] = G[\mathrm{dB}_d] + 2.15 \tag{2.53}$$

3. When the reference antenna is a Hertzian dipole or short vertical conductor (monopole) much shorter than one-quarter of the RF wavelength, and normal to the surface of perfectly conducting plane containing the given direction, then the gain is denoted by G_v and known as short vertical/Hertzian dipole-related gain. Between Hertzian dipole-related and isotropic gains of a given antenna, the following relation exists:

$$G[\mathrm{dB}_i] = G[\mathrm{dB}_v] + 4.8 \tag{2.54}$$

Usual applications of the mentioned gains are:

1. G_i at UHF, SHF, and EHF bands
2. G_d at VHF and UHF bands
3. G_v at LF and MF bands

2.11.2 ERP and EIRP

Equivalent radiated power, ERP, includes all gain and loss factors on the transmitting side and usually expressed in dB_m or dB_w. In fact, ERP is the product of TX output power and antenna gain in the desired direction by taking into account all losses regarding to RF feeder, connectors, etc., simply expressed by:

$$\mathrm{ERP} = \frac{G_t \cdot P_t}{L_t} \tag{2.55}$$

Reference antenna in the above expression is half wave dipole and its logarithmic form is:

$$\mathrm{ERP}[\mathrm{dB}_m] = P_t[\mathrm{dB}_m] + G_t[\mathrm{dB}_d] - L_t[\mathrm{dB}] \tag{2.56}$$

In the case of selecting isotropic antenna as reference, then it is called equivalent isotropic radiated power denoted by EIRP and expressed by:

$$\mathrm{EIRP}[\mathrm{dB}_m] = P_t[\mathrm{dB}_m] + G_t[\mathrm{dB}_i] - L_t[\mathrm{dB}], \quad \text{or} \tag{2.57}$$

$$\mathrm{EIRP}[\mathrm{dB}_w] = P_t[\mathrm{dB}_w] + G_t[\mathrm{dB}_d] - L_t[\mathrm{dB}] \tag{2.58}$$

2.11.3 Electric Field Intensity

Electric field intensity can be expressed versus EIRP. To find its relation first it should be noted that:

$$W = R_e\left\{\bar{E} \times \bar{H}\right\} = \frac{|E_d^2|}{\eta_0} \tag{2.59}$$

In line-of-sight radio propagation in free space, the power flux density at a distance d is:

$$W = \frac{P_t \cdot G_t}{L_t \cdot 4\pi d^2} = \frac{\text{EIRP}}{4\pi d^2} \tag{2.60}$$

Considering $\eta_0 = 120\pi$ in free space and using the last two formulas:

$$\frac{|E_d|^2}{\eta_0} = \frac{P_t \cdot G_t}{L_t \cdot 4\pi d^2} = \frac{\text{EIRP}}{4\pi d^2} \tag{2.61}$$

$$\Rightarrow \quad |E_d| = \frac{\sqrt{30\ \text{EIRP}}}{d} \tag{2.62}$$

It is noted that in (2.62) numerical (not logarithmic) value of EIRP shall be employed in proper system of units.

Example 2.8. Radiowaves are radiated by a 10 W transmitter connected to a 5 dB_i antenna:

1. Find EIRP if feeder loss is 2 dB
2. Find $|E_d|$ and W at a location of 8 km from TX

Solution. 1.

$$\text{EIRP}[\text{dB}_w] = P_t[\text{dB}_w] + G_t[\text{dB}_i] - L_t[\text{dB}] = 13\,\text{dB}_w$$
$$\Rightarrow \quad \text{EIRP} = \text{Antilog}13 = 20\,\text{W}$$

2. Applying (2.62) and $\eta_0 = 377\,\Omega$:

$$|E_d| = \frac{\sqrt{30 \times 20}}{8000} = 3.06 \times 10^{-3}\,\text{V/m} = 3.06\,\text{mV/m}$$
$$W = \frac{1}{2\eta_0}|E_d|^2 \quad \Rightarrow \quad W = 12.4\,\text{nW/m}^2$$

■

2.12 Transmission Loss

2.12.1 Loss Terms in Radio Links

Radiowaves propagating between transmitting and receiving antennas, in addition to free-space loss, are subject to excess attenuations including, but not limited to, the following items:

- RF feeder loss
- Antenna gain/loss
- Propagation mechanism losses
- Depolarization loss

For actual calculations and radio design, all factors shall be taken into account. To describe and standardize the terminology and notations employed to characterize transmission loss and its component, ITU-R under Recommendation No. P.341 has defined the concept of transmission loss for radio links.

As shown on Fig. 2.7, the following types of losses are indicated:

- Free-space loss, FSL of L_{bf}
- Basic transmission loss, L_b
- Transmission loss, L
- System loss, L_s
- Total loss, L_t

Full definitions are given in ITU-R, P.341 for each of the above terms.

2.12.2 Basic Transmission Loss

Free-space loss as permanent radiowave loss is calculated by formulas stated in (2.40)–(2.42). In actual transmission condition, some other attenuation factors are imposed on radiowaves due to medium effects. Sum of FSL and medium loss L_m is defined as basic transmission loss L_b:

$$L_b = \mathrm{FSL} \times L_m \tag{2.63}$$

The above formula in logarithmic form is:

$$L_b[\mathrm{dB}] = \mathrm{FSL}[\mathrm{dB}] + L_m[\mathrm{dB}] \tag{2.64}$$

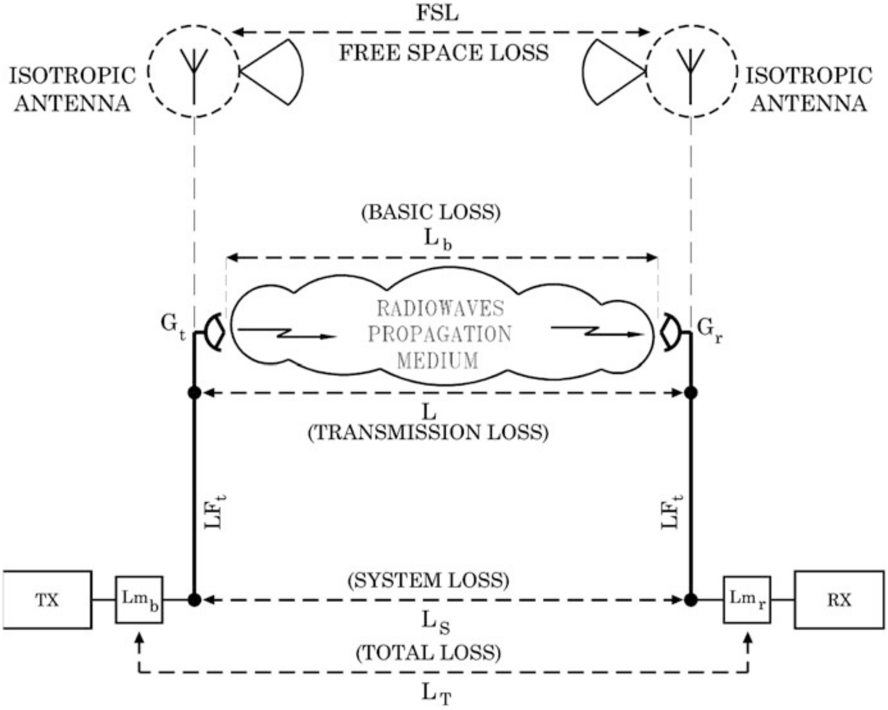

Fig. 2.7 ITU-based concept of transmission loss

A number of medium losses are:

- Atmospheric absorption loss due to gases, vapor, and aerosols
- Reflection loss, including focusing or defocusing due to curvature of reflecting layer
- Scattering of radiowaves due to irregularities in the atmospheric refractive index or by hydrometeors
- Diffraction loss due to obstructions
- Radio precipitation due to rain and snow
- Temporal climatic effects such as fog and cloud
- Antenna to medium coupling loss
- Polarization coupling loss
- Multipath adverse effects

By considering TX and RX antennas, then transmission loss L is calculated:

$$L[\mathrm{dB}] = L_b[\mathrm{dB}] - G_t[\mathrm{dB}_i] - G_r[\mathrm{dB}_i] \tag{2.65}$$

2.12.3 System and Total Losses

In accordance with ITU transmission loss concept, system loss L_s is defined as the following ratio:

$$L_s[\mathrm{dB}] = 10\ \log\left(\frac{P_t}{P_a}\right), \tag{2.66}$$

where

P_t: Transmitter power delivered to the input of TX antenna
P_a: Received signal level (RSL) at the output of RX antenna

Combining the mentioned relation yields:

$$L_s[\mathrm{dB}] = L[\mathrm{dB}] + L_{tc}[\mathrm{dB}] + L_{rc}[d] = P_t[\mathrm{dB}_m] - P_a[\mathrm{dB}_m] \tag{2.67}$$

Total loss L_t is defined as ratio of signal levels at selected points within transmitter and receiver systems. Exact points shall be indicated to avoid misunderstanding.

Example 2.9. A radio link is characterized by:

$$\mathrm{FSL} = 128\,\mathrm{dB},\ L_b = 135\,\mathrm{dB},\ L_c = L_{tc} + L_{rc} = 5\,\mathrm{dB},\ G_t = G_r = 30\,\mathrm{dB}_i$$

1. Find medium loss
2. Find P_t for received signal level of $-60\,\mathrm{dB}_m$

Solution. 1.

$$L_m[\mathrm{dB}] = L_b - \mathrm{FSL} = 7\,\mathrm{dB}$$
$$L_m = \text{Antilog } 7 = 5$$

Thus medium attenuates radiowave five times more.

2.

$$P_t[\mathrm{dB}_m] - P_r[\mathrm{dB}_m] = L_c[\mathrm{dB}] + L_b[\mathrm{dB}] - G_t[\mathrm{dB}_i] - G_r[\mathrm{dB}_i]$$
$$P_t + 60 = 5 + 135 - 30 - 30 \quad \Rightarrow \quad P_t[\mathrm{dB}_m] = 20\,\mathrm{dB}_m$$
$$P_t = \text{Antilog } 20 \quad \Rightarrow \quad P_t = 100\,\mathrm{mW}$$

■

2.13 Radio Ray Path and K-Factor

2.13.1 *Curvature of Ray Path*

Radiowaves passing through the Earth atmosphere are continually refracted by it and related aerosols. By increasing the height, air density gradually decrease resulting in variations of the refraction index. As indicated in Fig. 2.8, due to the refraction effects, the ray path will deviate from geometric straight line and will follow a curved path.

Instead of actual Earth radius, R_e, by assuming an equivalent value denoted by R'_e, the relative ray path will be a straight line. To calculate curvature of the ray path, as shown on Fig. 2.9, air is divided into a lot of thin layers with roughly constant value of refraction index.

Ray path in the atmosphere satisfies the following relation:

$$n\, R_e \sin\varphi = cte \tag{2.68}$$

Referring to Fig. 2.9, and the given notations, simple calculations result in:

$$AB = R(d\varphi) = \frac{dh}{\cos(\varphi_i + d\varphi)} \tag{2.69}$$

$$R = \frac{dh}{\cos\varphi_i \cdot d\varphi} \tag{2.70}$$

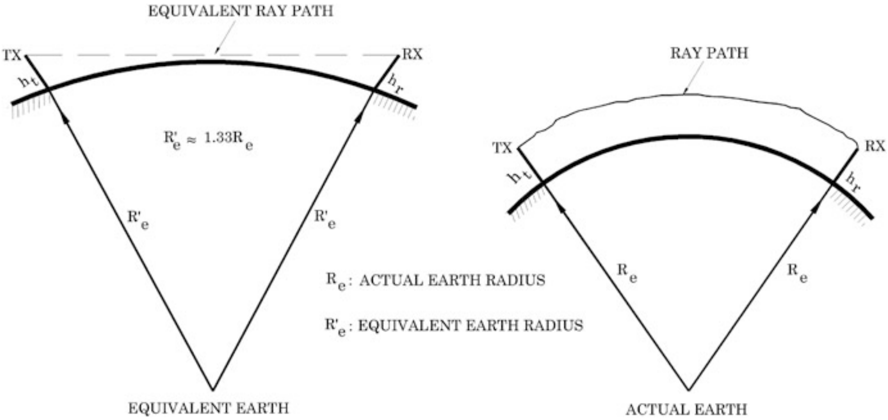

Fig. 2.8 Actual and equivalent ray path

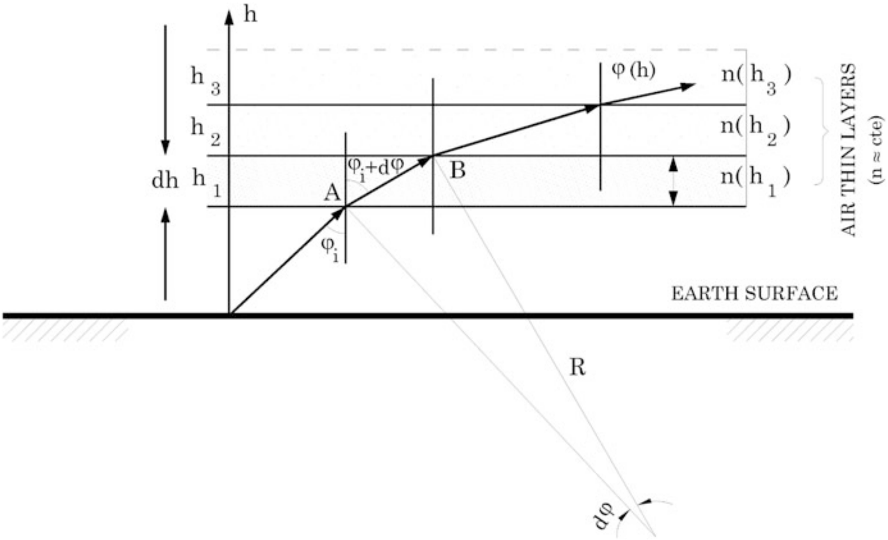

Fig. 2.9 Curvature of ray path

Applying condition set by (2.68):

$$\begin{aligned} n\sin\varphi_i &= (n+dn)\sin(\varphi_i+d\varphi)\\ &= n\sin\varphi_i\cos d\varphi + n\cos\varphi_i\sin d\varphi + dn\sin\varphi_i\cos d\varphi + dn\cos\varphi_i\sin d\varphi \end{aligned} \tag{2.71}$$

Assuming that $\cos(d\varphi) = 1, \sin(d\varphi) = d\varphi$, then (2.71) yields:

$$n\cos\varphi_i \cdot d\varphi = -dn\sin\varphi_i \tag{2.72}$$

$$\Rightarrow \quad \cos\varphi_i \cdot d\varphi = -\frac{dn}{n}\sin\varphi_i \tag{2.73}$$

Relations (2.70) and (2.73) result in:

$$R = dh/\left(-\frac{dn}{n}\sin\varphi_i\right) = -n/\left(\sin\varphi_i \cdot \frac{dn}{dh}\right) \tag{2.74}$$

$$\frac{dn}{dh} < 0 \quad \Rightarrow \quad R = n/\left|\frac{dn}{dh}\right| \cdot \sin\varphi_i \tag{2.75}$$

In line-of-sight radio links in troposphere such as microwave links, usually $\varphi_i \approx \pi/2$ and $\sin\varphi_i \approx 1$; thus:

$$R = n/\left|\frac{dn}{dh}\right| \tag{2.76}$$

For standard troposphere and based on normal variation of n, ray path curvature radius R is approximately 25,000 km.

Example 2.10. How much is the radiowave curvature radius if refraction indices are 1.00025 and 1.00023 at the heights of 1 km and 1.5 km, respectively.

Solution.

$$\Delta n = 1.00025 - 1.00023 = 2 \times 10^{-5}$$

$$\Delta h = 1.5 - 1 = 0.5\,\text{km} = 500\,\text{m}$$

$$\frac{dn}{dh} = \frac{\Delta n}{\Delta h} = 4 \times 10^{-8}$$

$$R = n\Big/\left|\frac{dn}{dh}\right| \quad \Rightarrow \quad R = \frac{1.00026}{4 \times 10^{-8}} = 25{,}006\,\text{km}$$

■

2.13.2 K-Factor

In line-of-sight radio link design, the preference is to have straight line for ray path. This virtual assumption is possible by considering an equivalent Earth radius R'_e. Referring to Fig. 2.10, there are two alternatives to meet this requirement.

In order to have similar conclusion, relative curvature is required to be equal. Due to inverse dependence between curvature of each curve with its radius, we have:

$$\frac{1}{R_e} - \frac{1}{R} = \frac{1}{R'_e} - \frac{1}{R'} \tag{2.77}$$

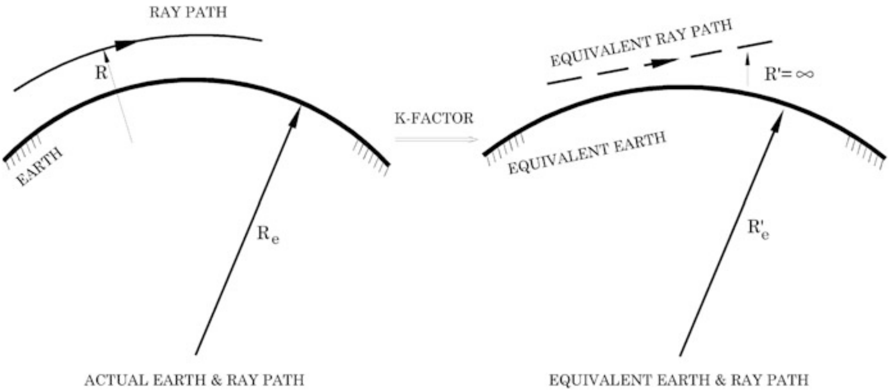

Fig. 2.10 Actual and equivalent earth and ray path

In this last expression, R_e and R'_e are actual and equivalent radii of Earth, while R and R' are actual and equivalent radii of the path, respectively. It is required that $R' = \infty$, thus:

$$R' = \infty \quad \Rightarrow \quad R'_e = \frac{R \cdot R_e}{R - R_e} \tag{2.78}$$

K-factor is defined as the ratio of equivalent radius of Earth to its actual value R_e:

$$K = \frac{R'_e}{R_e} = \frac{R}{R - R_e} \tag{2.79}$$

Based on standard values for $R = 25{,}000\,\text{km}$ and $R_e = 6370\,\text{km}$, the standard value of K-factor is 4/3 = 1.33. Also, the relation of K-factor with vertical gradient of air refraction index may be derived as follows:

$$K = \left(1 + R_e \frac{dn}{dh}\right)^{-1} \tag{2.80}$$

Example 2.11. Calculate K, R'_e, and R' for $R = 25{,}000\,\text{km}$ and $R_e = 6370\,\text{km}$.

Solution.

$$K = \frac{R}{R - R_e} = \frac{25{,}000}{25{,}000 - 6370} = 1.342$$

$$R'_e = KR_e = 1.342 \times 6370 \approx 8548\,\text{km}$$

$$\frac{1}{R'} = \frac{1}{R'_e} - \frac{1}{R_e} + \frac{1}{R} \quad \Rightarrow \quad R' \approx \infty$$

■

2.14 Summary

A number of basic principles including the following issues were dealt within this chapter:

- Transmission media and related characteristics having significant impacts on radiowave propagation
- Maxwell and wave equations in general forms focusing on the simplest form and plane radiowaves
- EM spectrum and the portion of it dedicated to radiowaves
- Media effects on radiowaves listed and parameters related to media such as α, γ, η, k, and refractive index as well as relevant formulas

- Polarization of radiowaves, either linear or nonlinear
- Free-space loss and the related formulas including ITU-R recommended expressions
- Equivalent radiated power in different forms including ERP and EIRP
- Transmission loss of different categories based on ITU definition including free-space, transmission, system, and total losses
- Effects of air refractivity and ray path curvature in line-of-sight radiocommunications
- K-factor and equivalent Earth radius

2.15 Exercises

Question

1. Prepare a list containing parameters related to transmission medium and indicate normal ranges of those parameters for available common media.
2. Specify propagation parameter and its related units.
3. By simple calculations, show that radiowaves for frequencies more than 100 kHz cannot pass through metallic sheets. Verify your response by calculating penetration depth in copper sheet of 2 mm thickness at $f_1 = 100\,\text{kHz}$ and $f_2 = 10\,\text{GHz}$.
4. Determine main reasons why radiocommunications is not possible in frequencies less than 10 kHz or more than 100 GHz.
5. Define radiowave polarization and indicate its types.
6. Prepare a report on applications of different types of polarization in radio systems.
7. Indicate the portion of the following radiowaves which may be received by a horizontally polarized antenna:

    - Vertical polarized radiowaves
    - Horizontal polarized radiowaves
    - Circular polarized radiowaves

    Prove your response with proper calculations.
8. Repeat question 7 for RHCP antenna receiving LHCP, RHEP, and vertically polarized radio waves.
9. Define peak power flux density and state its formula and relation with the mean value.
10. Referring to the ITU-based concept of transmission loss, determine their normal rough values for LOS microwave links working at 8 GHz and satellite links working in Ku band.
11. Define EIRP by specifying its formula in logarithmic form. Determine maximum value of EIRP in $\text{dB}_m$for the following cases:

  - $G_a = 52\,\mathrm{dB}_i, \quad P_t = 1.5\,\mathrm{kW}$
  - $G_a = 38\,\mathrm{dB}_i, \quad P_t = 500\,\mathrm{mW}$
  - $G_a = 10\,\mathrm{dB}_d, \quad P_t = 20\,\mathrm{W}$

12. Define K-factor and study about its application in radiocommunications.
13. Define actual and equivalent Earth radius and find its relations. Indicate ray path in each of them.
14. Applying Maxwell's equations and EM theory, extract the radiowave equations in lossy and lossless media.
15. Describe characteristics of a plane wave propagating in Z-direction.
16. How much is the radiowave velocity in atmosphere? State its relation with media characteristics.

Problems

1. A radiowave characterized by $\bar{E} = \hat{\alpha_y} 80\ \cos(10^6 t)\ \mathrm{V/m}$ is propagating over land with $\epsilon_r = 12,\ \mu_r = 1$ and $\sigma = 0.005\,\mathrm{S/m}$.

- Calculate propagation constants including $\alpha, \beta, \gamma, \eta, \lambda$, and V
- Find penetration depth (δ) and the depth at which the amplitude reduces to its half value.

2. Repeat problem 1 for $\bar{E} = \hat{\alpha_x} 10 \sin(10^5 \pi t)\ \mathrm{V/m}$ propagating in seawater $\epsilon_r = 81,\ \mu_r = 1$, and $\sigma = 4\,\mathrm{S/m}$. Also calculate water conductivity for $f_1 = 10\,\mathrm{kHz}$, $f_2 = 10\,\mathrm{MHz}$, and $f_3 = 10\,\mathrm{GHz}$.

3. For radiowaves with frequencies from 150 MHz to 4.2 GHz, determine upper and lower extremes of wavelength in a medium with $\epsilon_r = 72$ and $\mu_r = 1$.

4. Determine the polarization of a plane wave propagating in Z-direction with the following components:

$$E_x = 2\cos\omega t, \quad E_y = 3\sin\omega t$$

5. Find the polarization of radiowave specified by:

$$\bar{E} = \left[(2 + 3j)\hat{\alpha_x} + (3 - 2j)\hat{\alpha_y}\right] e^{-j\beta z}$$

6. A radiowave propagating in free space is specified by the following expression:

$$\bar{E} = \tfrac{1}{2}\left[\left(2\sqrt{3} - j\right)\hat{\alpha_x} + \left(2 - j\sqrt{3}\right)\hat{\alpha_y} + 2j\sqrt{3}\hat{\alpha_z}\right] e^{-j\frac{2\pi}{100}\left(\sqrt{3}+3y+2z\right)}$$

Find free-space loss at a distance $d_1 = 25\,\mathrm{km}$ for $f = 4\,\mathrm{GHz}$.
At a remote location $d_2 = 2\,d_1$, how much FSL will increase?

7. Effective amplitude of electric field at radiation source is 100 V/m and its value at a location 8 km far from the radiating source is $200\,\mu\mathrm{V/m}$. At frequency $f = 300\,\mathrm{MHz}$, find:

- Free-space loss, FSL
- Transmission basic loss
- Transmitting power of the source and receiving power at the distant location.

8. A 400 MHz radiowave with 200 V/m effective amplitude vertically penetrates inside seawater with $\epsilon_r = 81$, $\mu_r = 1$, and $\sigma = 4$ S/m.

- Find velocity and wavelength in the sea
- Calculate penetration depth
- Calculate electric field amplitude at the depth of 1 cm and also at 1 m

9. 500 mW output power of a microwave transmitter is connected to 40 dB_i directional antenna via a feeder with 6 dB loss.

- Find receiving power and electric field amplitude at a distance of 40 km in line-of-sight condition.
- Assuming total path loss equal to 140 dB, is it possible to detect the received signal by a receiver with $-80\,\text{dB}_m$ threshold level connecting to an omnidirectional antenna ($G = 0\,\text{dB}_i$) via RF feeder with 2 dB loss?
- Calculate antenna gain required for receiving a signal with 30 dB more power than threshold level.

10. Calculate free space and basic transmission losses for:

- $d = 25\,\text{km}, \quad f = 420\,\text{MHz}, \quad L_p = 15\,\text{dB}$
- $d = 30\,\text{km}, \quad f = 7.5\,\text{MHz}, \quad L_p = 4\,\text{dB}$

11. Find equivalent radiated power for 2 W transmitter connected by an RF feeder with $L_f = 5$ loss to an antenna with $G_i = 1000$. How much are amplitude of E-field at locations of 1 and 5 km away from the transmitter?

12. Solve the example (2.7) for $f = 2.5$ GHz, $P_t = 2$ W, and $P_r = -88\,\text{dB}_m$.

13. Solve the example (2.8) for $P_t = 20$ W and $G_a = 8\,\text{dB}_i$.

14. Solve the example (2.11) for ray path curvature radius $R = 24{,}000$ km.

15. Consider $R = 26{,}333$ km for radius of ray path curvature and calculate:

- K-factor
- Earth equivalent radius
- For K-factor variation in the range of 0.9–1.3 (due to variations of air refractive index), find minimum and maximum value of Earth equivalent radius.

Chapter 3
Radiowave Propagation in Troposphere

3.1 Introduction

Most of the radio transmissions are carried out in the lower layers of the Earth atmosphere and in fact in the troposphere. Some of radio systems in point-to-point, point-to-multipoint, and point-to-area types include line-of-sight radio links in UHF, SHF, and EHF bands, mobile radio networks in VHF and UHF bands, and TV and FM audio broadcasting. Due to vast usage of these communication systems, the study of the troposphere layer and its impacts on wave propagation is extremely important to radio experts and scientists.

In addition to these systems in which both sides of their transmission links are located in the troposphere layer, there are some other communication systems that one side is located in this layer, so they are somehow, but not as much as the above-mentioned systems, affected by this layer. Some examples of these systems are satellite communications for voice, video, and data, navigational aids, search and rescue (SAR), positioning and telemetry, ionospheric communications in HF and MF bands, as well as space communication systems.

There are a number of natural phenomena that occur in the path of radio waves and affect the signal level, quality, and performance. Considering these facts, recognition, study, and survey of these phenomena are very important and will be thoroughly investigated in this chapter; in addition, some useful tables and graphs related to this topic are also presented.

Basically, the wave propagation phenomena are affected by one of or a set of the following main factors:

- The Earth and its natural and physical properties such as bulge, roughness, structure, material, and flatness.
- Environmental conditions such as temperature, humidity, stable atmosphere composition, and air molecules such as oxygen, nitrogen, and water vapor.

A. Ghasemi et al., *Propagation Engineering in Wireless Communications*,
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- Atmospheric climate phenomena such as wind, storm, dust, thunderstorm, cloud, rain, snow, and hail.
- Celestial phenomena such as magnetic storms, sun-spots, diurnal, and seasonal effects.
- Artificial and man-made items such as skyscrapers, chemical particles, and gases generated by large factories and urban facilities.

The effects of the above-mentioned phenomena mostly depend on the frequency of wave. Therefore, recognition of these phenomena and their impacts on wave propagation is important to combat their adverse effects and find suitable counter measures.

The objective of this chapter is to provide the reader with a very clear impression and accurate perception of the principles, basics, and effects of these phenomena such as average rain quantity. The effects of these phenomena can be listed as wave reflection, diffraction, refraction, multipath fading, deviation in wave path, and Fresnel zones. Details of each system specific of these effects will be discussed in the relevant chapters.

Recently, several study topics and research projects have been defined by ITU in order to recognize the wave propagation behavior in the Earth atmosphere. The results of these studies are collected and provided in a set of ITU recommendations, called P series. A complete list of these recommendations and their subjects is presented in Appendix B at the end of this book. It is notable that some of the reports and recommendations are currently under revision by ITU-R study groups.

3.2 Earth Atmosphere

3.2.1 Major Parameters

The Earth atmosphere consists of several molecules including oxygen, nitrogen, carbonic compounds, inert gases, and water vapor. The amount, combination, and distribution of these compounds are affected by natural phenomena like solar effects, different seasons, spinal and orbital movement of the Earth, sky turbulences, as well as activities and changes made in the Earth surface by creatures, animals, plants, and internal activities inside it.

The Earth atmosphere in the troposphere layer is mainly defined by three key factors as specified below:

1. Height above mean sea level denoted by h in m
2. Temperature in terms of Kelvin denoted by $T(h)$
3. Humidity or water vapor pressure in terms of millibar denoted by $e(h)$
4. Atmospheric pressure in terms of millibar denoted by $P(h)$

3.2.2 Lower Part of Troposphere

Considering the key role of the troposphere in radio-communications, the standard values of its major parameters for the lower part are defined as follows:

- About 1000 mbar pressure in sea level
- Temperature around 17 °C equivalent to 290 K
- Relative humidity of RH = 60 %
- Pressure variation rate equal to $\frac{dP}{dh} = 12\,\mathrm{mb}/100\,\mathrm{m}$
- Temperature variation rate equal to $0.65\,°\mathrm{C}/100\,\mathrm{m}$

The major parameters of the troposphere layer are functions of altitude and comply with the following equations for heights less than 2 km above sea level:

$$T(h) = 290 - 6.5h \tag{3.1}$$

$$e(h) = 8 - 3h \tag{3.2}$$

$$P(h) = 950 - 117h \tag{3.3}$$

Where h is height in terms of kilometer, T is temperature in terms of Kelvin, and e and P are in terms of mbar. μ_r is almost constant and equal to 1 in the Earth atmosphere but ϵ_r is a variable and depends on the troposphere characteristics according to the following equation:

$$\epsilon_r = 1 + \frac{155.1}{T}\left[P + \frac{4810e}{T}\right] \times 10^{-6} \tag{3.4}$$

The following equalities hold at the sea level and altitudes less than 1 km. Using the above formula, the value of ϵ_r at sea level and 1 km high is:

$$h = 0 \quad \Rightarrow \quad \epsilon_{r(0)} = 1.00057$$

$$h = 1 \quad \Rightarrow \quad \epsilon_{r(1)} = 1.000502$$

Comparing $\epsilon_{r(0)}$ and $\epsilon_{r(1)}$ shows that changes in ϵ_r in the troposphere layer are negligible for the total altitude of changes in the range of 2 km.

3.2.3 Standard Earth Atmosphere

The standard Earth atmosphere is defined in order to make it possible to calculate the radio-wave loss due to gas compounds in the Earth atmosphere and also to define the temperature, atmospheric pressure, and water vapor pressure versus altitude. After a long survey and thorough study based on ITU-R, P.835-8 recommendation, finally, the reference atmosphere condition is defined according to the reference location of

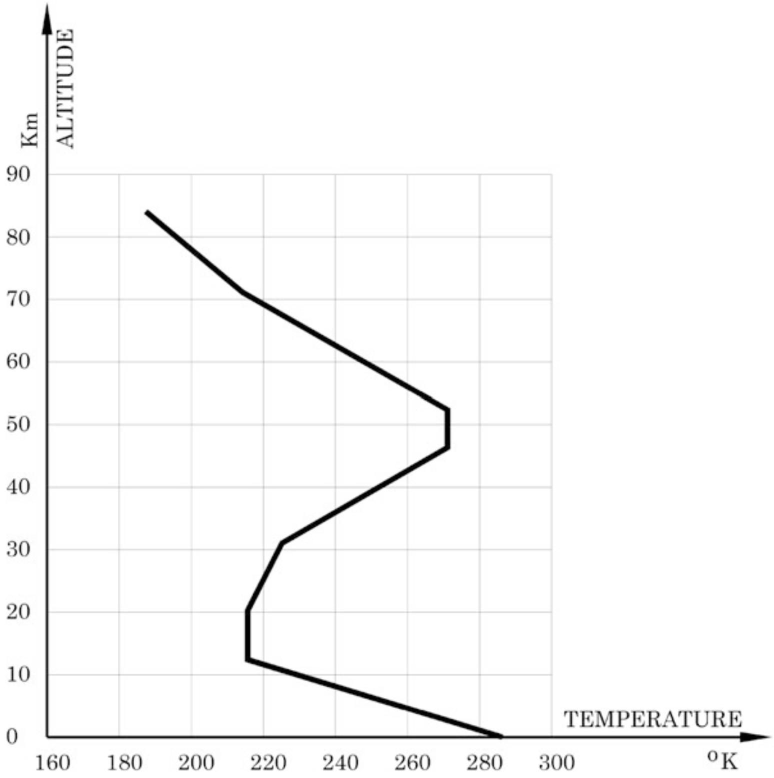

Fig. 3.1 Atmosphere temperature variations of standard earth (Ref.: ITU-R, P-835)

the United States standard atmosphere. In this standard, the temperature and Earth surface pressure are equal to:

$$P_0 = 1013.25\,\text{hpa}, \quad T_0 = 288.15\,\text{K}$$

Based on this definition, the Earth atmosphere is divided into seven consecutive layers. The temperature variation rates of these layers versus altitude are depicted in Fig. 3.1. According to this model, the relationship between temperature rate $T(h)$ in terms of Kelvin and altitude h in terms of kilometer is equal to:

$$T(h) = T_i + L_i(h - H_i) \tag{3.5}$$

$$T_i = T(H_i) \tag{3.6}$$

where L_i is the gradient of temperature in altitude H_i, and its values for different layers and heights are presented in Table 3.1. Also, atmospheric pressure depends on the location (latitude) and the date (the season of the year) in addition to the height.

Table 3.1 Temperature gradient in atmosphere sub-layers

i	H_i(km)	Temperature gradient, L_i(K/km)
0	0	−6.5
1	11	0
2	20	+1.0
3	32	+2.8
4	47	0
5	51	−2.8
6	71	−2.0
7	85	–

Thermodynamic stability of atmosphere breaks down in the heights above 85 km, and the hydrostatic equations that are the basis of these equations are not valid anymore. Changes in water vapor distribution of atmosphere are approximated by the following equation:

$$\rho(h) = \rho_0 e^{(-h/h_0)} \tag{3.7}$$

where $h_0 = 2\,\text{km}$ and $\rho_0 = 7.5\,\text{g/m}^3$ and similar to the atmospheric pressure, the water vapor pressure also depends on the location, height, and the season of the year. It should be noted that the water vapor pressure decreases exponentially as height increases up to a particular value of the height.

To calculate attenuation caused by other atmospheric gases, similar procedure as expressed by Eq. (3.7) may be followed with $h_0 = 6\,\text{km}$.

3.2.4 Non-standard Atmospheric Parameters

Exact value of the major parameters of the atmosphere for other areas of the Earth (other than the USA) can be determined by practical experiments. Since this practical survey has not done for most areas of the Earth, so, ITU-R has defined special equations to calculate $T(h)$, $P(h)$, and $\rho(h)$ for different periods of year and heights up to 100 km above mean sea level (AMSL) based on the following classification:

- Areas located at northern/southern latitudes less than 22°
- Areas located at middle latitude range between 22 and 45° in either northern or southern hemispheres.
- Areas located at northern/southern latitudes greater than 45°

Detailed information of these equations is presented in ITU-R P.835-3 recommendation.

Example 3.1. Calculate the major atmospheric parameters for locations of height range between 2 and 5 km in summer with the following two approaches:

1. Using the basic formulas
2. Using the following new formulas

$$T(h) = 294.98 - 5.22h - 0.07h^2$$

$$P(h) = 1012.82 - 111.56h + 3.86h^2$$

$$\rho(h) = 14.35e^{(-0.42h - 0.02h^2 + 0.001h^3)}$$

Solution. 1. Applying Eqs. (3.1)–(3.3) which are valid for heights bellow 2 km, we have:

$$T(2) = 290 - 6.5 \times 2 = 277\,\text{K}$$

$$P(2) = 950 - 117 \times 2 = 716\,\text{mbar}$$

$$e(2) = 8 - 3 \times 2 = 2\,\text{mbar}$$

2. Using the proposed formulas for height equal to 2 km, it yields:

$$T'(2) = 294.98 - 5.22 \times 2 - 0.07 \times 4 = 284.3\,\text{K}$$

$$P'(2) = 1012.82 - 111.56 \times 2 + 3.86 \times 4 = 805.14\,\text{hPa}$$

$$\rho'(2) = 14.35e^{(-0.42 \times 2 - 0.02 \times 4 + 0.001 \times 8)} = 5.76\,\text{hPa}$$

Applying these formulas for height equal to 5 km, the following results are obtained:

$$T'(5) = 267.13\,\text{K}$$

$$P'(5) = 551.52\,\text{hPa}$$

$$\rho'(5) = 1.2\,\text{hPa}$$

■

3.3 Radiowave Refraction

The radio-waves propagating in the Earth atmosphere always experience the wave refraction phenomenon. As the height increases, the air density and consequently its refractive index decrease. This nonhomogeneous characteristic of air in the atmosphere causes deviation in wave propagation path, so they do not travel further on a straight direction. When the rate of refraction index changes linearly, the ray path would be an arc of a circle with constant radius.

3.3.1 Refractive Index of Air

The refractive index of every environment is related to its relative permittivity according to the following equation:

$$n = \sqrt{\epsilon_r} \tag{3.8}$$

Therefore, the refractive index of the air, where ϵ_r is found from Eq. (3.4), is:

$$n = \sqrt{\epsilon_r} = \left\{1 + \frac{155.1}{T}\left[P + \frac{4810e}{T}\right] \times 10^{-6}\right\}^{1/2} \tag{3.9}$$

Using the binomial expansion for the above expression and selecting the first two terms, we have:

$$n = 1 + \frac{77.6}{T}\left[P + \frac{4810e}{T}\right] \times 10^{-6} \tag{3.10}$$

Because it is difficult to use the value of this term in the calculations, another parameter called refractivity number and denoted by N is defined as follows:

$$N = (n - 1) \times 10^6 \tag{3.11}$$

According to this definition, the refractivity number of the air at sea level and altitude equal to 1 km is:

$$h = 0 \quad \Rightarrow \quad N_0 = 289$$
$$h = 1 \quad \Rightarrow \quad N_1 = 251$$

Also a new parameter called modified refractive index and denoted by n_M is defined according to the following equation:

$$n_M = n + h/R_e \tag{3.12}$$

In the last equation, n is refractive index of the air, h is the height of the location, and R_e is the actual Earth radius where the last two parameters have the same unit. There is another parameter called refractive modulus and is defined according to the following equations:

$$M = (n_M - 1) \times 10^6 \tag{3.13}$$

$$M = N + 10^6 h/R_e \tag{3.14}$$

Example 3.2. Calculate the value of n and N for air at the altitude of 2 km based on the formula (3.4) at the standard atmosphere conditions.

Solution.

$$h = 2\,\text{km} \quad \Rightarrow \quad T = 277\,\text{K},\ \rho = 716\,\text{mb},\ e = 2\,\text{mb}$$

$$\epsilon_r = 1 + \frac{151.1}{277}\left(716 + \frac{4810 \times 2}{277}\right) \times 10^{-6} = 1.00042$$

$$n = \sqrt{\epsilon_r} = 1.00021$$

$$N = (n-1) \times 10^6 \quad \Rightarrow \quad N = 210$$

■

3.3.2 *Wave Path and Effective Earth Radius*

Radiowave refraction in the Earth atmosphere has several effects on its propagation and can result in transition of the wave over the horizon. It can be assigned to a straight line for propagation path of waves provided that a new equivalent radius is assumed for the Earth which is denoted by R'_e instead of the actual Earth radius.

Formula for the equivalent radius of the Earth was derived in Chap. 2. For standard atmosphere, calculations resulted in $R'_e = 8500\,\text{km}$, while actual radius of the Earth is 6370 km.

3.4 K-Factor

3.4.1 *Definition*

To analyze radiowave path clearance in line-of-sight links, it is preferred to assume straight path for radiowave propagation rather than its actual curved trajectory. This assumption can be satisfied by considering a factor named K-factor which is defined as the ratio of the equivalent Earth radius (R'_e) to its actual value (R_e).

K-factor is a dynamic parameter which is dependent on refractive index variations of the ray path in the atmosphere. Some relations and formulas for K-factor have been stated in Chap. 2. K-factor values shall be taken into account where radiowave path calculations are necessary.

3.4.2 Variation Range of K-Factor

K-factor values have a key role in radio link design. Its actual values and range of variations are related to the site-specific conditions. The following different values of K-factor are used to analyze propagation phenomena in the terrestrial line-of-sight radio links.

- The standard value of K which equals to $4/3$ is generally used to set path clearance criteria of LOS propagation.
- The lowest value of K, for instance, $K = 2/3$, causes the effective Earth radius to decrease, and consequently the ray path between two particular points with a specific distance has more bulges on it. Therefore, higher transmitter and receiver antennas are required for LOS transmission resulting in higher implementation cost. For the minimum value of K, the least path clearance of LOS transmission is obtained, so, suitable predictions and calculations should be performed to avoid obstruction of the paths.
- The high values of K, for instance $K = 2$ or more, causes an abnormal long range of the LOS path that results in undesired effects of formation of reflective paths.
- The effective value of K which is called K_e is based on an approximate graph for conventional environmental conditions and is widely used in fixed radio system design at frequency range of 2–10 GHz. Figure 3.2 shows K_e variation for terrestrial LOS links based on ITU-R recommendations.

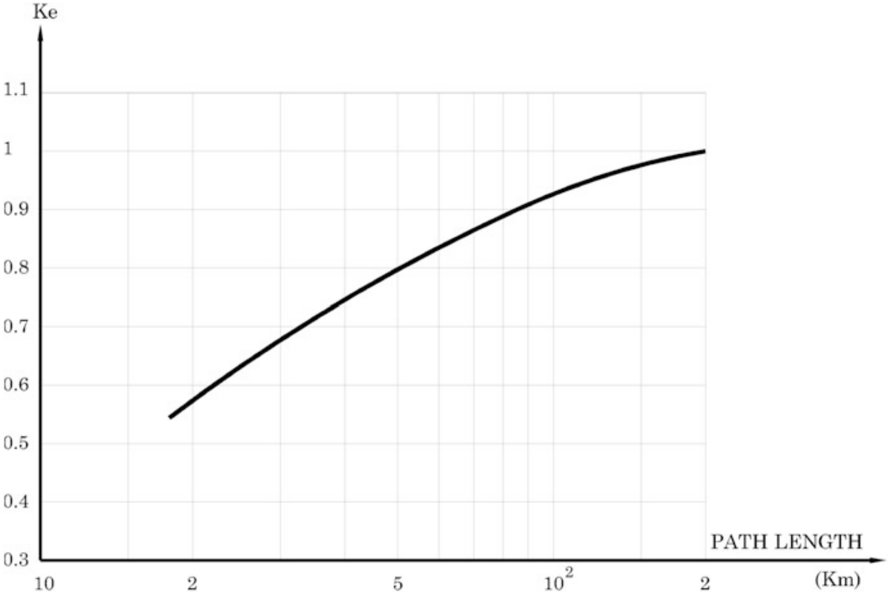

Fig. 3.2 Variation of K_e

Table 3.2 Ray path condition versus N'

REFRACTION TYPE	N'=dN/dh	K FACTOR	RADIUS OF RAY R(Km)	EQUIVALENT EARTH RADIUS R'e(Km)	RAY PROFILE VS EARTH
SUB-REFRACTION	N'>0	——	——	——	
LESS THAN STANDARD	N'=0	K=1	R= ∞	$R'_e > R_e$	
STANDARD	N'=-39	$K=\frac{4}{3}$	R=2500	$R'_e = 8500$	
CRITICAL	N'=-157	K= ∞	$R=R_e$	$R'_e = \infty$	
SUPER REFRACTION	N'<-157	K<0	$R<R_e$	$R'_e < R_e$	

As shown in Table 3.2, the value of K depends on some factors such as the rate of N variation, curvature radius, and relative wave path length. If the vertical gradient of refractivity number is presented by $N' = dN/dh$, so different conditions based on this value can be classified as follows:

- $N' > 0$: Sub-refraction condition
- $N' = -39$: Standard refraction condition
- $N' = -157$: Critical condition ($K = \infty$) which means that wave propagates parallel to the Earth surface
- $N' < -157$: Super refraction condition which causes duct effect

To provide a good perception of this subject, the relative status of propagating wave and Earth surface is depicted in Fig. 3.3 for three cases of the Earth including actual, equivalent and flat conditions.

3.4.3 The Earth Bulge

Bulge between transmitter and receiver is defined as the height of every point of the equivalent Earth regarding the straight line of TR according to Fig. 3.4. This parameter can be calculated as:

$$h_K = \frac{500\, d_1\, d_2}{K\, R_e} \tag{3.15}$$

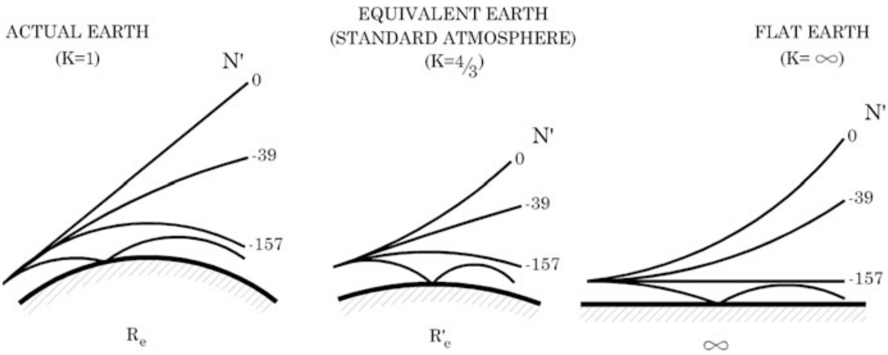

Fig. 3.3 Relative status of ray path and the Earth

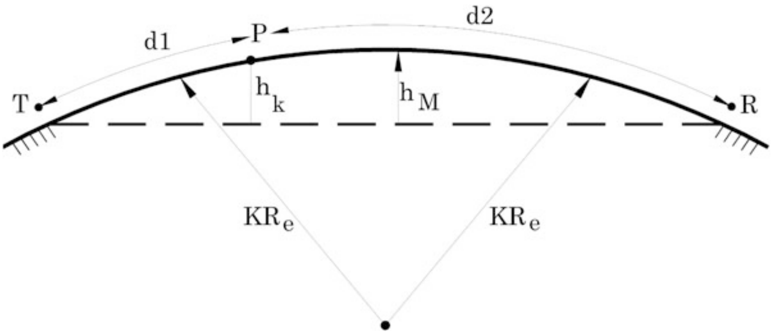

Fig. 3.4 Earth bulge geometry

The maximum value of bulge occurs in the middle of the path which equals to:

$$h_M = \frac{125\, d^2}{K\, R_e} \tag{3.16}$$

In the last two equations, h is the bulge of Earth in meter, R_e is the actual Earth radius, d_1 and d_2 are distances between point P from the transmitter and the receiver respectively, and d is the sum of d_1 and d_2, all in km. According to the mentioned equations, the value of bulge is inversely proportional to the value of K. Therefore, as K decreases, the bulge of the Earth and the required height of transmitter and receiver antennas increase.

Example 3.3. If the relative permittivity of a medium is 1.001, the vertical gradient of refractive index is -35×10^{-6}, and the distance between transmitter and receiver is 20 km,

1. Find the bulge value in the middle of the path.

2. Compare the bulge value in a point with 5 km distance from transmitter in this medium with the same point in standard atmosphere condition.

Solution. 1.

$$\epsilon_r = 1.001 \quad n = \sqrt{\epsilon_r} = 1.0005$$

$$R = \frac{n}{|\frac{dn}{dh}|} = \frac{1.0005}{35 \times 10^{-6}} = 28{,}586\,\text{km}$$

$$K = \frac{R}{R - R_e} = 1.287$$

Earth bulge value in the middle of path according to Eq. (3.16) is:

$$h_M = \frac{125 \times 20^2}{1.287 \times 6370} = 6.1\,\text{m}$$

2. The bulge value for the given point is:

$$d_1 = 5\,\text{km}, \quad d_2 = 15\,\text{km}$$

$$h_1 = \frac{500 \times 5 \times 15}{1.287 \times 6370} = 4.58\,\text{m}$$

The bulge value for the standard atmosphere condition ($K = 1.3333$) at the same point is:

$$h_1' = \frac{500 \times 5 \times 15}{1.333 \times 6370} = 4.42\,\text{m}$$

Therefore, the bulge value for this medium in the given point is 16 cm greater than the corresponding value at standard atmosphere. ■

3.4.4 Radio Horizon

Distance between transmitter antenna and horizon, R_t, called radar horizon as shown in Fig. 3.5 and considering that $R_e' \gg h_t$, R_t, can be expressed by:

$$R_t = \sqrt{(R_e' + h_t)^2 - (R_e')^2} \approx \sqrt{2\,R_e' h_t} \tag{3.17}$$

and similarly the distance between receiver antenna and horizon, R_r, considering that $R_e' \gg h_r$ can be expressed by:

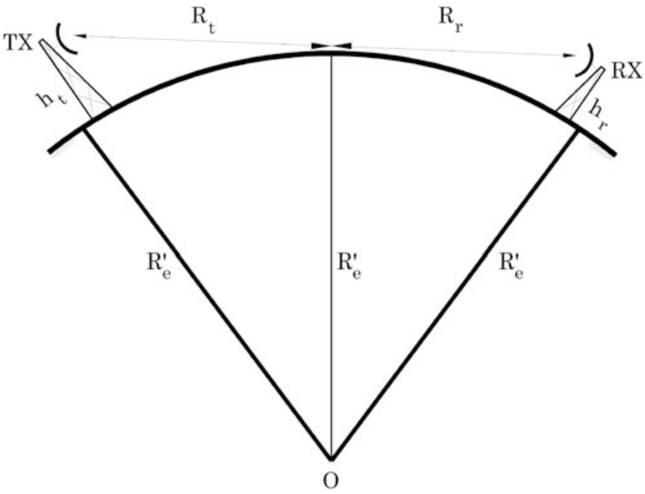

Fig. 3.5 Radio horizon

$$R_r = \sqrt{2R'_e h_r} \tag{3.18}$$

The sum of the two distances is called radio horizon and is equal to:

$$R_{\mathrm{RH}} = \sqrt{2R'_e h_t} + \sqrt{2R'_e h_r} \tag{3.19}$$

For the standard condition ($K = 1.33$) where the equivalent Earth radius is $R'_e = 8500\,\mathrm{km}$, the equation of radio horizon is simplified to

$$R_{\mathrm{RH}}[\mathrm{km}] = 4.12[\sqrt{h_t(m)} + \sqrt{h_r(m)}] \tag{3.20}$$

Example 3.4. A radar antenna is 24 m high. Find the region that the objects with height greater than 15 m are detectable by this type of antenna. Find the results for two cases of standard K value and $K = 1$.

Solution. 1.

$$K = 1.33 \;\Rightarrow\; R_{\mathrm{RH}}[\mathrm{km}] = 4.12[\sqrt{24} + \sqrt{15}] = 36.1\,\mathrm{km}$$

2.

$$K = 1 \;\Rightarrow\; R'_e = KR_e = 6370\,\mathrm{km}$$

$$R'_{\mathrm{RH}} = \sqrt{2R'_e h_1} + \sqrt{2R'_e h_2} = 31.3\,\mathrm{km}$$

■

Fig. 3.6 Basic types of atmospheric ducts

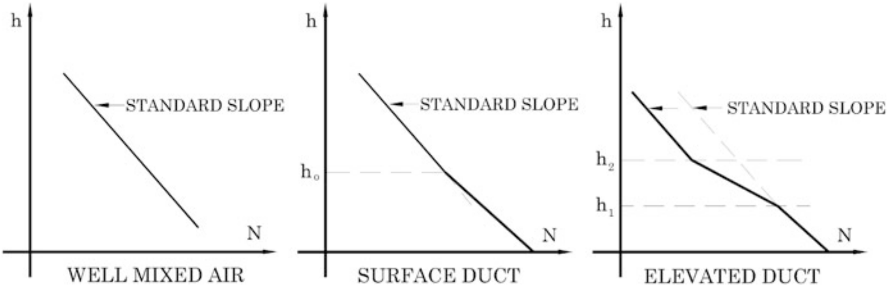

Fig. 3.7 Variation of N as a function of *h* in duct formation

3.4.5 Atmospheric Duct

3.4.5.1 Duct Formation

Sometimes the standard atmospheric model does not apply in certain parts of the world due to inhomogeneous atmosphere named ducting phenomenon. These abnormal conditions occur where the refractive index of air decreases nonlinearly with height, where a more dense air formed over a less dense layer.

As shown in Fig. 3.6 and under special conditions, the incident rays will be refracted back to the surface of the Earth, and this process will be repeated again several times, until it reaches the receiving point within a thin layer of the atmosphere near the Earth. This phenomenon is known as ducting, and the confined wave will propagate over a long distance in a guided medium suffering much less attenuation than for free-space propagation.

As stated in Sect. 3.4.2 and Table 3.2, refraction also occurs in the duct which is categorized into two main types:

- Surface duct
- Elevated duct

The main reason of duct formation is temperature inversion phenomenon. The rate of N versus h for three cases of standard, surface duct and elevated duct is depicted in Fig. 3.7.

The following facts are considered regarding air ducts and their impacts:

- Ducts are often formed because of water vapor in the air, so it commonly occurs above the lakes, seas, and oceans.
- This phenomenon occurs at the height less than 1.5 km and rarely occurs in mountains and highlands.
- Thickness of ducts is in a wide range of one meter up to several hundred meters and it could be a temporary or permanent duct.
- In case of severe winds or rainfalls, ducts disappear because the air layers are merged and mixed.
- Radiowaves at UHF or higher bands can propagate inside the ducts.
- In case of putting transmitter and receiver antennas inside the duct, radiowaves propagate a longer distance.
- High coupling loss is imposed on radiowaves when antennas are located outside the duct.

3.4.5.2 Theory of Propagation in Atmospheric Ducts

Based on the Snell's law for stratified media with flat Earth assumption, as depicted in Fig. 3.8a, the following relation holds:

$$n(z)\ \cdot \sin\varphi_i(z) = cte \tag{3.21}$$

where $n(z)$ is the air refractive index and $\varphi_i(z)$ is incident angle at the height z. In the actual case for a spherical Earth with spherically stratified atmosphere as shown in Fig. 3.8b, the Snell's law is converted to the following form:

$$n(z)\ \cdot\ (R_e + z)\sin\varphi_i(z) = cte \tag{3.22}$$

Differentiating the above function with respect to z yields:

$$d\varphi_i = -\tan\varphi_i\left(\frac{dn}{n} + \frac{dz}{R_e + z}\right) \tag{3.23}$$

$$\varphi_i \approx 90^\circ \quad \Rightarrow \quad \frac{dn}{n} + \frac{dz}{R_e + z}\ \approx\ 0 \tag{3.24}$$

Using the above equation, the gradient of refractive index is:

$$\frac{dn}{dz} = -\frac{n}{R_e + z} \tag{3.25}$$

$$z << R_e \quad \Rightarrow \quad \frac{dn}{dz} \approx -\frac{n}{R_e} \tag{3.26}$$

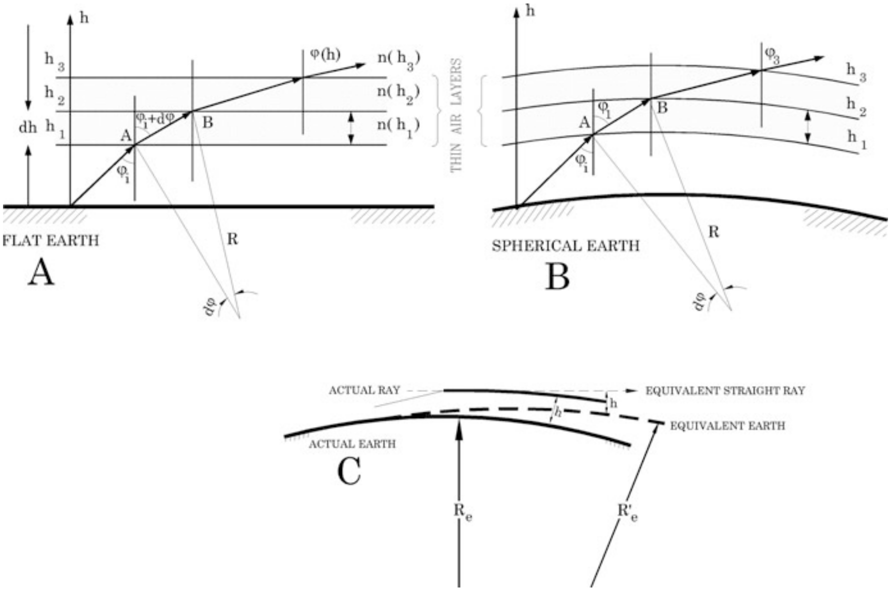

Fig. 3.8 Radiowave propagation in atmosphere

For the standard atmosphere, the average value of the gradient of refractive index is smaller and can be considered as $\frac{1}{R'_e}$ for which R'_e is the equivalent Earth radius:

$$\frac{dn}{dz} = -\frac{1}{R'_e} \tag{3.27}$$

It should be noted that the ratio of R_e and R'_e is known as K-factor in the line-of-sight radio links:

$$K = \frac{R'_e}{R_e} \tag{3.28}$$

Ray Path in Duct

To find ray trajectory inside the air ducts, similar procedure as used in optical fiber cables and dielectric slabs can be followed. For more details, reference is made to the relevant professional books in these fields.

Modified index of refraction inside atmospheric ducts has parabolic profile with typical value for N_0 and N_1 equal to 1 and $1.3 \times 10^{-7}/\text{m}^2$, respectively, which may be expressed as follows:

$$N(z) = N_0 + N_1 \cdot (h - z) \cdot z \tag{3.29}$$

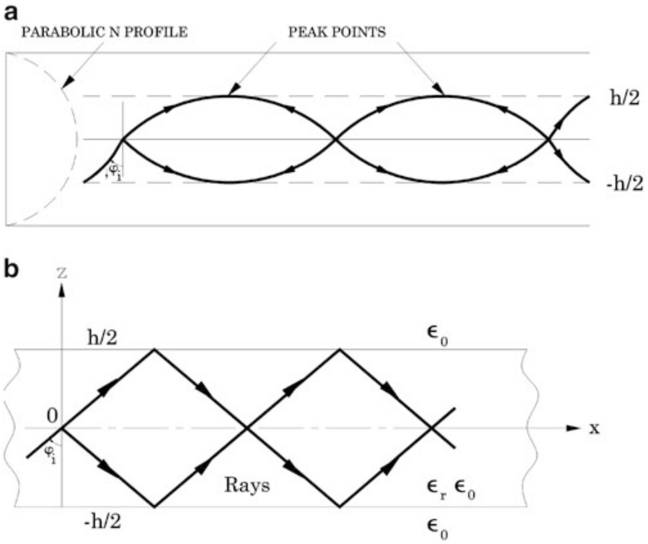

Fig. 3.9 Ray path in the duct. (**a**) Ray path in air duct. (**b**) Equivalent dielectric slab model

As shown in Fig. 3.9a, radiated ray has an incident angle of φ_i. At the height of $z > h/2$, the angle φ is given by Snell's law satisfying the following relation:

$$N(z) \cdot \sin\varphi = N(h/2)\sin\varphi_i \tag{3.30}$$

At the peak points where $\varphi = \pi/2$, the above relation is simplified to:

$$N(z) = N(h/2)\sin\varphi_i \tag{3.31}$$

Solving Eq. (3.29) for peak point ($z = z_P$) results in:

$$z_P = \frac{h}{2}\left[1 + \left(1 + \frac{4N_0}{h^2 N_1}\right)^{1/2} \cdot (1 - \sin\varphi_i)^{1/2}\right] \tag{3.32}$$

For small φ_i, when it is less than a critical value φ_c, the ray will penetrate through the duct and cannot be trapped. The critical φ_c is defined as the angle at which the ray is refracted at $z = h$ for $\varphi_i = \varphi_c$; thus, Eq. (3.32) is reduced to:

$$\sin\varphi_c = \frac{4N_0}{4N_0 + h^2 N_1} \tag{3.33}$$

With reference to Fig. 3.9, it is clear that all rays with $\varphi_i < \varphi_c$ are trapped, while only certain angles that depend on frequency correspond to the guided modes in the duct. The waveguiding mechanism of an atmospheric duct is similar to that of a dielectric slab but more complicated.

A dielectric slab is shown in Fig. 3.9b to which a TM mode with field components E_z, E_x, and H_y is applied. H_y component can be expressed as:

$$H_y = \begin{cases} A[e^{jkz\cos\varphi_i} + e^{-jkz\cos\varphi_i}]e^{-jkx\sin\varphi_i} & |z| < h/2 \\ Be^{-jk_0|z|\cos\varphi_t - jk_0 x\sin\varphi_t} & |z| > h/2 \end{cases} \tag{3.34}$$

In order to match the tangential components of electric field across the boundary surfaces $z = \pm h/2$ for all values of x, it is required that:

$$k_0 \sin\varphi_t = k\sin\varphi_i \tag{3.35}$$

Upward and downward propagation waves form a standing-wave solution in the z direction within slab. Such a solution is possible only if there is a complete reflection at each dielectric-air interface. This requires that the angle φ_i be greater than critical φ_c which is given by:

$$k\sin\varphi_c = k_0 \quad \Rightarrow \quad \varphi_t = 90^\circ \tag{3.36}$$

$\varphi_i > \varphi_c$ results in $\cos\varphi_t$ to be pure imaginary, thus the field outside the slab will be evanescent. For convenience let $k\sin\varphi_i = \beta$, $k\cos\varphi_i = \gamma = (k^2 - \beta^2)^{1/2}$, and $jk_0\cos\varphi_t = \alpha = (\beta^2 - k_0^2)^{1/2}$. The solution for H_y can then be expressed in the form:

$$H_y = \begin{cases} 2A\cos\gamma z e^{-j\beta x} & |z| < h/2 \\ Be^{-\alpha|z| - j\beta x} & |z| > h/2 \end{cases} \tag{3.37}$$

The x component of the electric field is given by:

$$j\omega\epsilon E_x = -\frac{\partial H_y}{\partial z}$$

Hence

$$E_x = \begin{cases} \left(\frac{2\gamma k_0^2 A}{j\omega\epsilon_0 k^2}\right)\sin\gamma z e^{-j\beta x} & |z| < h/2 \\ \left(\frac{\alpha\beta}{j\omega\epsilon_0}\right)e^{-\alpha z - j\beta x} & x > h/2 \end{cases} \tag{3.38}$$

Continuity of H_y and E_x at $z = h/2$ requires that:

$$\gamma\tan\gamma\frac{h}{2} = \frac{k}{k_0}\alpha \tag{3.39}$$

This characteristic equation, along with the following relationship:

$$\gamma^2 + \alpha^2 = K^2 - K_0^2 \tag{3.40}$$

determines the allowed values of γ and β that correspond to guided modes in the slab.

Example 3.5. Assuming $N_0 = 1$ and $N_1 = 1.3 \times 10^{-7}/\mathrm{m}^2$, find:

1. Critical angle φ_c for h = 20 m
2. h,φ_i for guided modes, $\alpha = 2.75$ and $\lambda_0 = 10\,\mathrm{cm}$.

Solution. 1. Using formula (3.33) for φ_c:

$$\sin\varphi_c = \frac{4}{4 + 400 \times 1.3 \times 10^{-7}} \quad \Rightarrow \varphi_c =$$

2. First β and γ shall be calculated:

$$\alpha^2 = B^2 - k_0^2 \quad \Rightarrow \quad \beta^2 =$$

$$\gamma^2 = k^2 - \beta^2 \quad \Rightarrow \quad \gamma^2 =$$

Equation (3.39) is used to calculate h which yields:

$$h = 4.72\,\mathrm{m}, \quad \text{and for } \varphi_i :$$

$$\cos\varphi_i = \frac{\gamma}{k} \quad \Rightarrow \quad \varphi_i = 89.47^\circ$$

■

3.4.5.3 Wave Propagation Inside the Duct

As stated before, air duct phenomenon occurs in the lower part of the troposphere when a dense and heavy layer of air is formed above a thin layer of air. This fact can be explained using the vertical gradient of the air refractivity number less than −157 N/km for this location.

The essence of ducts is important because of its effects on anomalous radiowave propagation, particularly on terrestrial or very low angle Earth-space links. Ducts provide a medium for radiowave signals with sufficiently high frequency to propagate far beyond their line-of-sight range. A potential drawback is the interference with other services. Air ducting also plays a key role in the occurrence of multipath interference.

Wave Elevation Angle

When a transmitter antenna is located inside a duct with horizontal layering, then the radio-waves with low elevation angles are trapped in the duct. For a simplified case of the surface duct with constant vertical gradient of refractive index, the critical angle α is defined in terms of gradient as follows:

$$\alpha = \sqrt{2 \times 10^{-6} \left| \frac{dM}{dh} \right| \times \Delta h} \tag{3.41}$$

$$M = N + \frac{1000h}{R_e} = (n - 1) \times 10^6 + \frac{1000h}{R_e} \tag{3.42}$$

$$\frac{dM}{dh} = \frac{dN}{dh} + \frac{1000}{R_e} \tag{3.43}$$

The parameters in the above equations are defined as follows:

- α: critical elevation angle of waves in radian
- M: Modified refractive index
- h: Elevation in meter
- R_e: The earth radius in km

In Fig. 3.10, the maximum elevation angle of the waves trapped inside the duct is shown for various duct thicknesses. This angle can be increased by:

- Decreasing the gradient of refractivity number (below −157 N/km)
- Increasing the duct thickness

Minimum Trapping Frequency

Duct formation does not necessarily imply efficient wave coupling and a long-distance propagation. In addition to the necessary condition of elevation angle of the antenna being less than the critical angle α, and also, the wave frequency should be greater than a particular value called critical frequency. The value of critical frequency is related to the duct physical thickness and air refractive index variations. If the wave frequency is less than the critical frequency, the wave cannot be transmitted effectively inside the duct and essentially no good coupling occurs. The critical frequency of tropospheric duct waves can be calculated using electromagnetic theory and its fundamental equations. The value of $f_{\min}$ for surface and elevated ducts versus different gradients of refractivity number is depicted in Fig. 3.11.

Example 3.6. The air refractivity gradient at the height of 20 m above ground level in a coastal area is −200 N/km, and consequently a surface duct is generated.

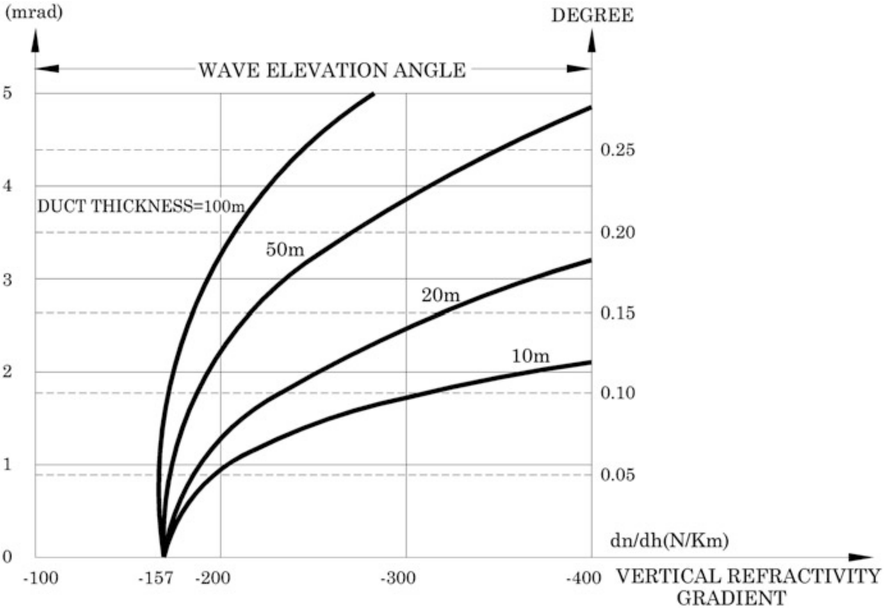

Fig. 3.10 Maximum elevation angle for coupling in air ducts (Ref: ITU-R, P.834)

1. Find the elevation angle of waves that can pass through the duct.
2. Find the elevation angle using the graph in Fig. 3.10.
3. Find the minimum frequency of coupling waves into the duct.

Solution. 1.

$$dN/dh = -200\,\mathrm{N/km} = -0.2\,\mathrm{N/m}$$

$$\frac{dM}{dh} = -0.2 + \frac{1000}{6370} = -0.043$$

$$\alpha = \sqrt{2 \times 10^{-6} \times 0.043 \times 20} = 1.31\,\mathrm{mrad} = 0.075°$$

2. Using the graph in Fig. 3.10 and for $N = -200$ N/km, it can be found that the critical angle is 0.074 mrad which is close to the calculated result.
3. Using Fig. 3.11, the minimum frequency required for coupling waves into the duct is 7 GHz. ■

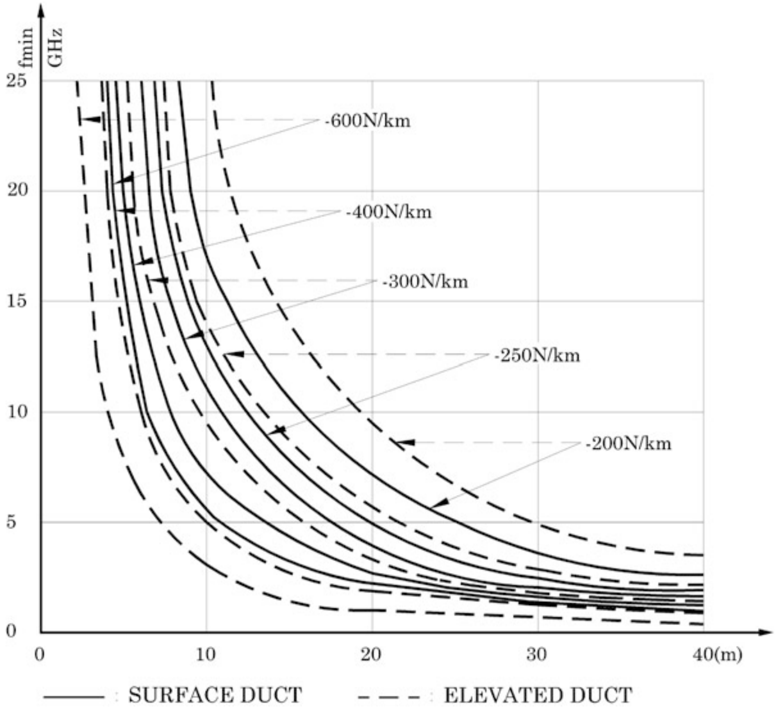

Fig. 3.11 Minimum coupling frequency in air ducts (Ref.: ITU-R, P-834)

3.5 Radiowave Attenuation in Troposphere

3.5.1 Introduction

In this section the attenuation caused by environmental phenomena such as rain, snow, hail, cloud, fog, and different particles and gases is investigated. These effects normally appear at frequency bands up to 100 GHz and affect most of radiocommunication systems. It should be noted that in addition to these losses, also the free-space loss discussed in previous chapter affects the received signal level.

3.5.2 Rain Attenuation

Rain attenuation occurs at all frequencies, but it is negligible at frequencies less than 8 GHz. In the frequency range of 8–10 GHz, the attenuation is small and is proportional to rainfall rate. At frequencies more than 10 GHz, this effect is considerable and should be taken into account for LOS link design.

For instance, the attenuation caused by rain with an intensity of 50 mm/h and 15 km path length is approximately equal to:

- 1 dB at 6 GHz
- 3 dB at 8 GHz
- 16 dB at 15 GHz

The rain attenuation is a function of frequency, shape and size of raindrops, instant rainfall intensity, path length influenced by rain, as well as type of wave polarization. So, an accurate statistics of rainfall data is required to calculate the attenuation. Some important notes in this regard are:

- While it rains heavily, there is no atmospheric multipath fading, so the assigned fade margin is used to compensate the rainfall attenuation.
- Antenna space diversity (SD) and frequency diversity (FD) techniques cannot compensate the rain attenuation.
- Appropriate diversity to avoid fading during severe rainfall is cross band diversity (CBD) which is very useful and prevents transmission interruption. For instance, 6 and 11 GHz frequency bands can be used as a CBD diversity. While attenuation caused by severe rainfall at 11 GHz frequency band is too high, the waves can easily propagate at 6 GHz band, since it suffers a very low rain attenuation.

A lot of researches have been done to calculate the attenuation of rainfall, and some achievements are presented in P series ITU-R recommendations including P.676, P.837, and P.838. A practical approach to calculate the rain attenuation is the procedure reported in ITU-R recommendation P.838. This procedure is explained through including the following steps:

Step 1: Rainfall intensity in mm/h for more than 0.01 % of time is determined using statistical data and is denoted by R or $R_{0.01}$. In lack of statistical data, approximate values of these parameters can be employed using the special graphs presented in ITU-R recommendation P.563.

Step 2: If the frequency band and wave polarization is known, K and α coefficients can be obtained using Table 3.3, and then the specific attenuation term γ_R in dB/km can be calculated using the following formula:

$$\gamma_R = K R^{\alpha} \tag{3.44}$$

Step 3: Equivalent path length which is part of path affected by rainfall and denoted by d_e can be calculated based on the following practical formula:

$$d_e = \frac{90}{90 + d} \times d \tag{3.45}$$

where d is the actual path length and d_e is the equivalent path length and both in km.

Table 3.3 K and α values (in terms of frequency)

α_V	α_H	K_V	K_H	Frequency (GHz)
0.8592	0.9691	0.0000308	0.0000259	1
0.9490	1.0664	0.0000998	0.0000847	2
1.2476	1.6009	0.0002461	0.0001071	4
1.5728	1.5900	0.0004871	0.0007056	6
1.4745	1.4810	0.001425	0.001915	7
1.3797	1.3905	0.003450	0.004115	8
1.2156	1.2517	0.01129	0.01217	10
1.1216	1.1825	0.2455	0.02386	12
1.0440	1.1233	0.05008	0.04481	15
0.9847	1.0568	0.09611	0.09164	20
0.9491	1.9991	0.1533	0.1571	25
1.000	1.021	0.167	0.187	30
0.8761	0.9047	0.3224	0.3374	35
0.8421	0.8673	0.4274	0.4431	40
0.8123	0.8355	0.5375	0.5521	45
0.7871	0.8084	0.6472	0.6600	50
0.7486	0.7656	0.8515	0.8606	60
0.7215	0.7345	1.0253	1.0315	70
0.7021	0.7115	1.1668	1.1704	80
0.6876	0.6944	1.2795	1.2807	90
0.6765	0.6815	1.3680	1.3671	100
0.6609	0.6640	1.4911	1.4866	120
0.6466	0.6494	1.5896	1.5823	150
0.6343	0.6382	1.6443	1.6378	200
0.6262	0.6296	1.6286	1.6286	300
0.6256	0.6262	1.5820	1.5860	400

Step 4: The attenuation factor for more than 0.01 % portion of time is calculated based on the following equation:

$$A_{0.01} = \gamma_R \cdot d_e \text{ [dB]} \tag{3.46}$$

In Table 3.3, the values of K and α are presented for vertical and horizontal polarizations at different frequencies.

Since there is no appropriate and perfect model to calculate the rain attenuation, several formulas are developed to estimate the attenuation based on the measurements. One of these formulas is:

$$\gamma = A\,R^B \tag{3.47}$$

In this formula, γ is the rain specific attenuation in dB/km and A and B are the coefficients defined by:

$$\mathbf{A} = \boldsymbol{\alpha}\mathbf{f}^{\boldsymbol{\alpha}} \tag{3.48}$$

$$a = 6.39 \times 10^{-5}, \quad \alpha = 2.03 \quad \text{for} \quad f < 2.9\,\text{GHz}$$

$$a = 4.21 \times 10^{-5}, \quad \alpha = 2.42 \quad \text{for} \quad 2.9\,\text{GHz} < f < 54\,\text{GHz}$$

$$a = 4.09 \times 10^{-5}, \quad \alpha = 0.699 \quad \text{for} \quad 54\,\text{GHz} < f < 180\,\text{GHz}$$

$$\mathbf{B} = \boldsymbol{\beta}\mathbf{f}^{\boldsymbol{\beta}} \tag{3.49}$$

$$b = 0.851, \quad \beta = 0.158 \quad \text{for} \quad f < 8.5\,\text{GHz}$$

$$b = 1.41, \quad \beta = -0.0779 \quad \text{for} \quad 8.5\,\text{GHz} < f < 25\,\text{GHz}$$

$$b = 2.63, \quad \alpha = 0.272 \quad \text{for} \quad 25\,\text{GHz} < f < 164\,\text{GHz}$$

Example 3.7. The path length of a microwave link operating at 18 GHz with vertical polarization is 30 km. If the rainfall intensity is 25 mm/h:

1. Calculate the rain specific attenuation.
2. Find the maximum rain attenuation.

Solution. 1. Using Table 3.3 and employing the interpolation method for vertical polarization, the following results can be obtained:

$$\alpha_V(15) = 1.128, \quad \alpha_V(20) = 1.065$$

$$\Rightarrow \quad \alpha_V(18) = 1.09$$

$$K_V(15) = 0.0335, \quad K_V(20) = 0.0691$$

$$\Rightarrow \quad K_V(18) = 0.0587$$

$$\gamma_R = K_V R^{\alpha_V} \quad \Rightarrow \quad \gamma_R = 1.96\,\text{dB/km}$$

2.

$$d = 30\,\text{km} \quad \Rightarrow \quad d_e = \frac{90}{90 + d} \times d \ = \ 22.5\,\text{km}$$

$$A = d_e \cdot \gamma_R \quad \Rightarrow \quad A \ = \ 44.1\,\text{dB}$$

■

3.5.3 Cloud and Fog Attenuation

3.5.3.1 Overall Considerations

Due to ever-increasing demand for radio-communications, utilizing higher-frequency bands, i.e., SHF and EHF bands, in microwave systems and satellite communications becomes more and more common. For cloud and fog attenuation at tera-hertz and optical links, reference is made in Chap. 8.

Generally, cloud and fog consist of very small drops with diameter less than 0.1 mm and can impair wave propagation at frequencies about 100 GHz with 3 mm wavelength. To determine the loss caused by cloud and fog, the amount of water in the unit volume should be determined. Cloud and fog loss can be evaluated based on the following formula:

$$\gamma_c = K_l \cdot M \tag{3.50}$$

where the parameters and their units in this formula are as follows:

γ_c: Specific attenuation of clouds or fog in dB/km
K_l: Specific attenuation index in $\frac{\mathrm{dB/km}}{\mathrm{g/m^3}}$
M: Water density of the cloud or fog

For frequencies bellow 10 GHz, the attenuation is totally negligible, and at a frequency range of 10–100 GHz it is small and proportional to the specific attenuation index which can be investigated if required. For frequencies higher than this range, the loss is really high and should be considered in calculations. Water density of fog in moderate cases with visibility range of about 300 m is $0.05\ \mathrm{g/m^3}$, and for thick fog with a visibility range of 50 m, it is about $0.5\ \mathrm{g/m^3}$.

3.5.3.2 Specific Attenuation Index

To calculate the specific attenuation index of cloud and fog, the following mathematical model which is based on Rayleigh distribution and electrical permittivity $\epsilon(f)$ model at frequencies up to 1000 GHz can be used:

$$K_l = \frac{0.819f}{\epsilon''(1+\eta^2)} \tag{3.51}$$

In the above equation, f is frequency in GHz and the water permittivity is a complex value.

In Fig. 3.12, the variation of K_l is depicted versus frequencies between 5 and 200 GHz and for a temperature range of $-8°$ to $+20\,°\mathrm{C}$. For clouds, the same graph should be used setting the temperature to $0\,°\mathrm{C}$.

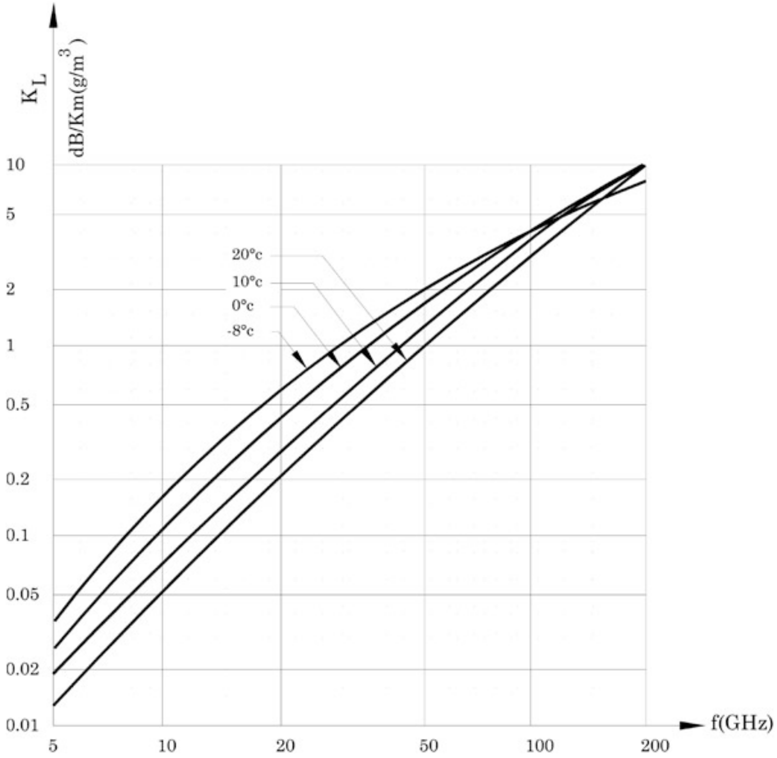

Fig. 3.12 K_l variation vs. frequency (Ref.: ITU-R, P-840)

3.5.3.3 Cloud Loss in Satellite Communication

Since cloud formation is not a deterministic process, it is necessary to have an estimation of its probability and the amount of water in it to calculate corresponding attenuation. In satellite communications, because of the position of stations with respect to the cloud, the radiowaves cross whole thickness of the clouds. So, the amount of water in the vertical cylinder of cloud with a cross section of 1 m^2 shall be measured or estimated for calculation of cloud attenuation. This value is denoted by L and stated in kg/m^2.

The statistical data of the amount of water in a unit cylinder and the location of that point including its longitude and latitude is required in order to calculate the cloud attenuation in a particular location.

These values can be obtained exactly by performing local measurements. However, it may be obtained using graphs provided in ITU-R recommendation P.840-3, when there is no measured data.

These graphs are provided for four nominal probabilities of 1 %, 5 %, 10 %, and 20 %. The graph corresponding to 10 % is shown in Fig. 3.13. For other values of probability, the latest ITU-R recommendation can be referred.

In this graph, the amount of water in unit cylinder of cloud in kg/m^2 and probability of 10 % is presented by counters for various locations in the world. The linear property of L and logarithmic relation of probability value can be considered in order to have a more accurate estimation of these values.

For terrestrial microwave transmission, where mainly the waves do not pass through the clouds, this effect can be calculated specifically considering Eq. (3.50).

Example 3.8. 1. Find the range of specific attenuation coefficient at the frequency band between 10 and 100 GHz using the graph of Fig. 3.12.

2. Find the specific attenuation coefficient for fog at 40 GHz for 20 °C temperature, and $M = 0.25\,\mathrm{g/m^3}$.

Solution. 1.

$$10\,\mathrm{GHz} \le f \le 100\,\mathrm{GHz} \overset{\text{Fig. 3.12}}{\Rightarrow} 0.06 \le K_l \le 4\,(\mathrm{dB/km})/(\mathrm{g/m^3})$$

2.

$$M = 0.1\,\mathrm{g/m^3} \overset{\text{Fig. 3.12}}{\Rightarrow} K_l = 0.7\,(\mathrm{dB/km})/(\mathrm{g/m^3})$$

■

3.5.4 Hail and Snow Attenuation

Because of saturation of frequencies bellow 30 GHz and tendency to use higher frequencies for new applications, especially by achievements in design and fabrication of RF components in EHF frequency band, it is worthy of doing further studies and researches for adverse effects of snow and hail on high-frequency radio-wave propagation. Major points of hail and snow impacts are outlined below:

- Effect of dry snow on frequencies less than 50 GHz is negligible. Although the wet snow (snow mixed with rain) has even more attenuation than the equivalent rain, undesired effects of snow and ice that are collected over parabolic antennas are more considerable than the effects of snow over the wave propagation paths. More details are given for snow attenuation in tera hertz frequency band in Chap. 9.
- Attenuation caused by hail is considerable even at frequencies less than 2 GHz, but considering the fact that the occurrence probability is too low, so its impact is very limited to the order of less than 0.001 % of time.

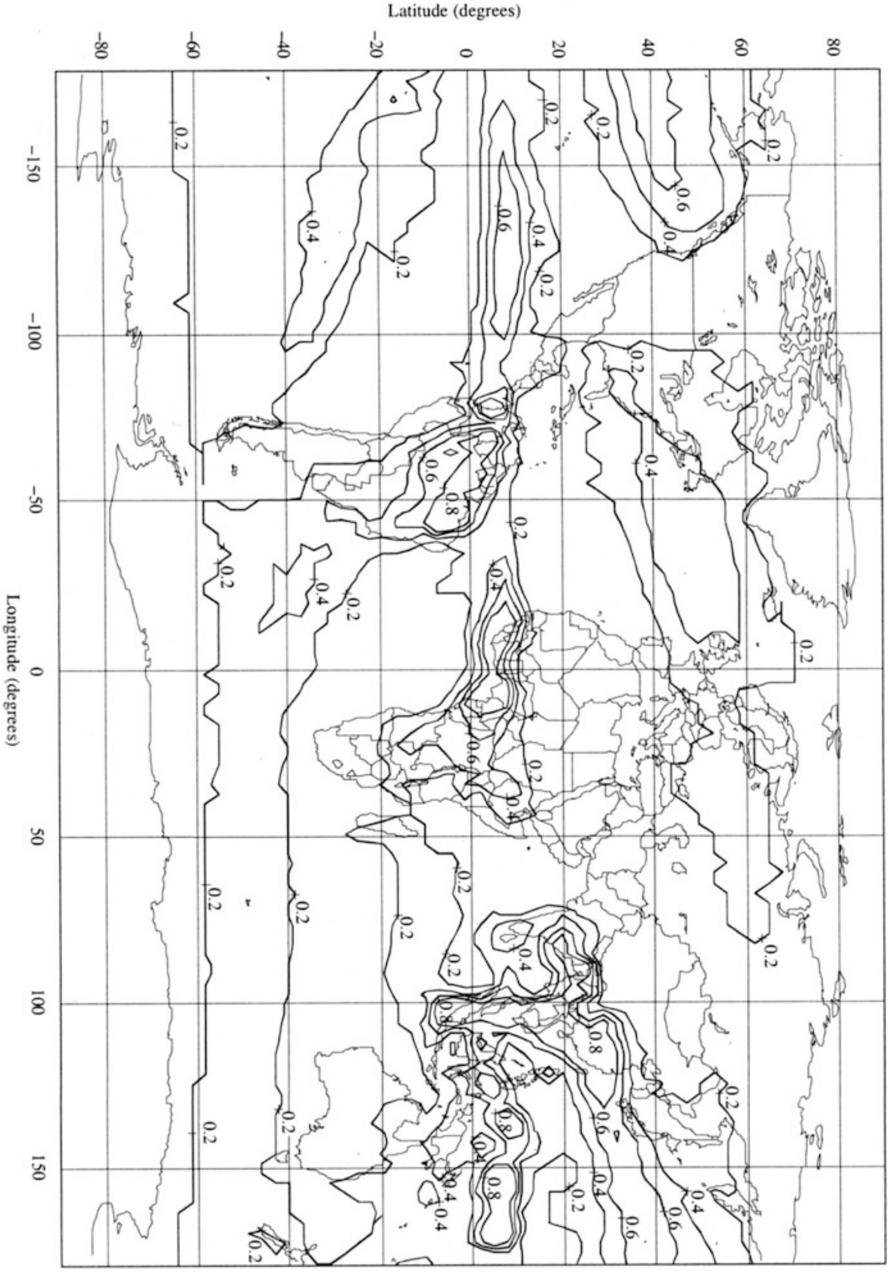

Fig. 3.13 Normalized total columnar of cloud liquid water in kg/m^2 exceeded for a percent of the year (Ref.: ITU-R, P-840)

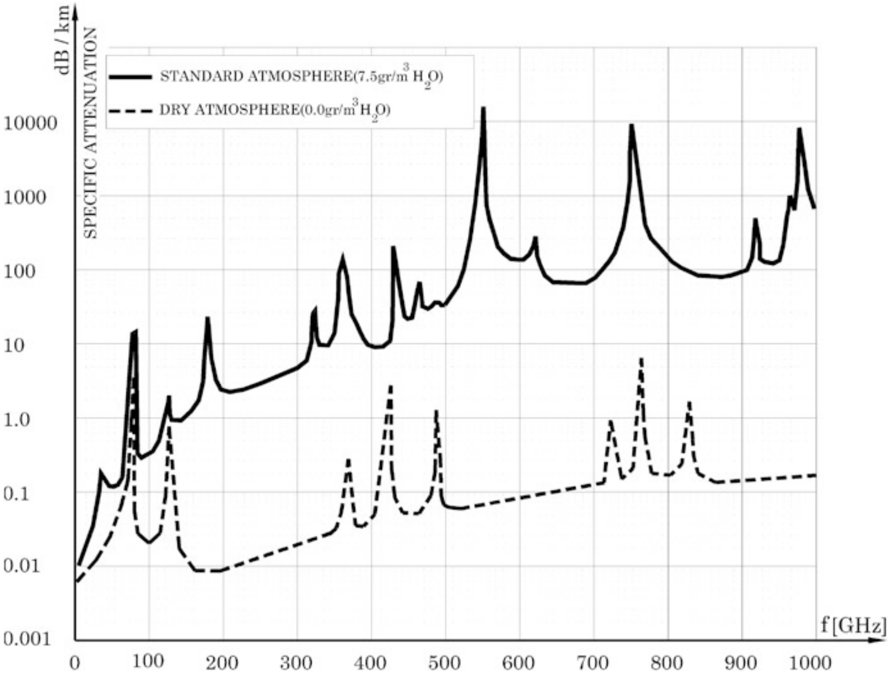

Fig. 3.14 Atmospheric water vapor and gases attenuation (Ref.: ITU-R, P-676)

3.5.5 *Aerosols*

In addition to cloud, fog, and some related tropospheric phenomena, there are other types of particles such as dust, sand, smoke, water vapor, and oxygen in the air. Major points in this field are outlined below:

- Sand and dust caused by storm impose negative impacts on the electromagnetic wave propagation. Laboratory experiments over radiowaves at the frequency of 10 GHz show that the loss caused by the dust with a density of $10^{-5}\,\mathrm{g/cm^3}$ is about 0.4 dB/km while it is 0.1 dB/km for the same density of sand particles.
- Impact of existing water vapor and oxygen in atmosphere is negligible at frequencies less than 20 GHz, and their specific attenuation coefficient at higher frequencies based on ITU-R recommendation P.676 is shown with the following graphs (Figs. 3.14 and 3.15).

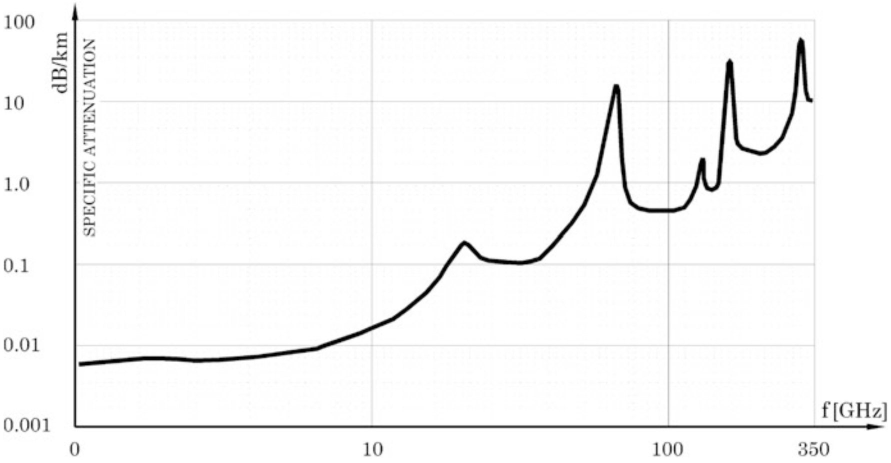

Fig. 3.15 Atmospheric total water vapor and gases attenuation (Ref.: ITU-R, P-676)

3.6 Radiowave Reflection

3.6.1 Reflection Equations

Reflection phenomenon occurs when electromagnetic waves encounter surface of different media. Reflection characteristic depends on the following factors:

- Incident angle
- Wave polarization
- Material of reflection surface
- Wave frequency
- Roughness of reflection surface

When the reflection surface is flat in comparison to the ray wavelength, the reflection occurs considerably. For instance, the wavelength with a frequency of 1 GHz is about 30 cm, so the surface with roughness less than 3 cm appears as a flat surface.

The reflection coefficient is defined as the ratio of the amplitude of reflected wave to the amplitude of incident wave and can be calculated according to the Snell's law and satisfying boundary conditions.

The reflection equations and formulas for horizontally and vertically polarized waves are stated in most of the electromagnetic books such as "Field and Wave Electromagnetic" by David. K. Cheng and "Advanced Engineering Electromagnetic" by C. Balanis. According to Fig. 3.16 and for angle of incident, reflection, refraction, and grazing which denoted by θ_i, θ_r, θ_t, and ψ, respectively, the reflection coefficient can be calculated as follows:

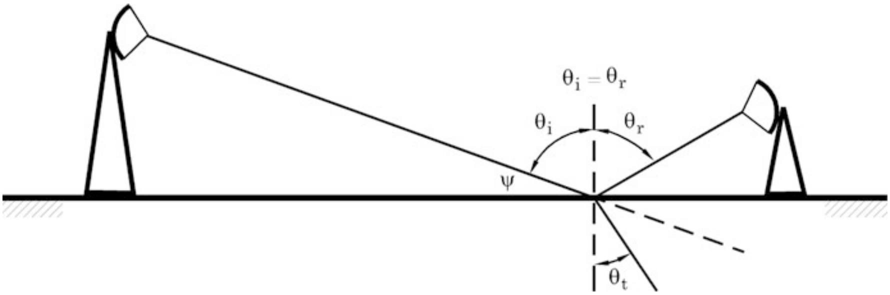

Fig. 3.16 Basic geometrical concept of radiowave reflection

$$\theta_i = \theta_r \tag{3.52}$$

$$R_H = \frac{\eta \cos\theta_i - \eta_0 \cos\theta_t}{\eta \cos\theta_v + \eta_0 \cos\theta_t} \tag{3.53}$$

$$R_V = \frac{\eta \cos\theta_t - \eta_0 \cos\theta_i}{\eta \cos\theta_t + \eta_0 \cos\theta_i} \tag{3.54}$$

In the above equations, R_V and R_H are reflection coefficients of horizontal and vertical polarizations, respectively, $\eta_0 = 120\pi$ is the intrinsic impedance of air, and η is the characteristic impedance of the second environment. ψ is the grazing angle and is equal to:

$$\psi = 90 - \theta_i \tag{3.55}$$

Generally, ϵ_r is a complex value which is defined as $\epsilon_{rc} = \epsilon_r - j\frac{\sigma}{\omega\epsilon_0}$ and μ_r equal to 1, therefore, it results in the following value for the medium characteristic impedance:

$$\eta = \sqrt{\frac{\mu}{\epsilon}} = \sqrt{\frac{\mu_0}{\epsilon_0(\epsilon_r - j\chi)}}, \quad \chi = \frac{\sigma}{\omega\epsilon_0} \tag{3.56}$$

Typical variation of amplitudes of reflection coefficients R_V and R_H versus incident angle and at different frequencies are depicted in Fig. 3.17. As it is shown in this graph, R_V has its minimum value for angles about 15°. In this situation, the incident wave is transferred almost perfectly, and no wave is reflected and the angle is called Brewster angle. The following facts about the reflection coefficient are important:

1. For vertical radiation, where $\theta_i = 0$, in other words $\psi = 90$:

$$R_H = R_V = \frac{\eta - \eta_0}{\eta + \eta_0} \tag{3.57}$$

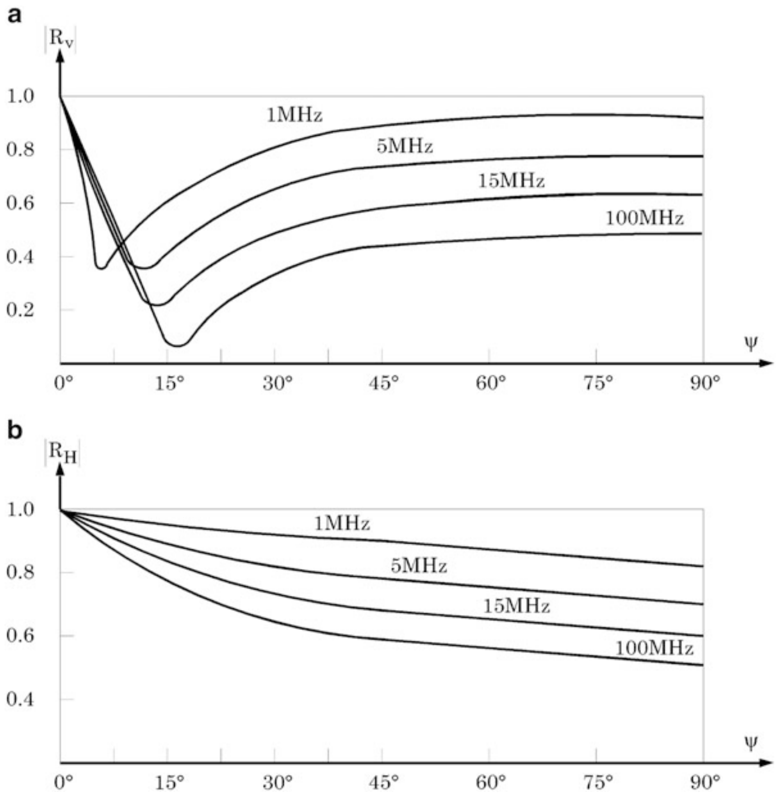

Fig. 3.17 Typical variation of reflection coefficient. (**a**) Vertical polarization. (**b**) Horizontal polarization

2. For tangential radiation where $\theta_i \approx 90$ and $\varphi \approx 0$:

$$R_H = R_V = -1 \tag{3.58}$$

3. According to Fig. 3.17, change of R_H versus ψ in the whole range is very low.
4. The value of R_V in a particular angle called Brewster angle is almost zero.
5. For lossy ground, the obtained results are valid and applicable provided that ϵ_0 is replaced by $\epsilon_c = \epsilon_0(\epsilon_r - j\frac{\sigma}{\omega\epsilon_0})$. In this case, the Brewster angle θ_B is converted to quasi-Brewster angle that means the reflection coefficient value is not zero, but it is a minimum value depending on σ and ω.

The other forms of reflection coefficients expressions are stated based on the grazing angle and can be simplified to the following forms by applying mathematical rules and relations between angles.

$$R_H = \frac{\sin\ \psi - \sqrt{(\epsilon_r - j\chi) - \cos^2\ \psi}}{\sin\ \psi + \sqrt{(\epsilon_r - j\chi) - \cos^2\ \psi}} \tag{3.59}$$

$$R_V = -\frac{(\epsilon_r - j\chi)\sin\ \psi - \sqrt{(\epsilon_r - j\chi) - \cos^2\ \psi}}{(\epsilon_r - j\chi)\sin\ \psi + \sqrt{(\epsilon_r - j\chi) - \cos^2\ \psi}} \tag{3.60}$$

Example 3.9. If the UHF and VHF waves impinge on the surface of calm sea with average roughness of 10 cm and $\epsilon_r = 75$

1. Examine that whether it can be assumed as a flat surface or not?
2. Find the reflection coefficient for horizontal and vertical angle of radiation ($\sigma = 4\,\text{S/m}, f = 5\,\text{GHz}$)
3. Find the vertical and horizontal reflection coefficient for grazing angle equal to 30° at a frequency of 10 GHz.

Solution. 1. For VHF waves, the wavelength is between 1 and 10 m and for UHF waves it is between 10 and 100 cm, so the calm sea surface appears flat for VHF and even low UHF frequencies, while it does not behave as a flat surface for high UHF frequencies.

2. For incident angle equal to 90 (which is equivalent to grazing angle of zero), it results:

$$R_H = R_V = -1$$

And for incident angle equal to 90°, η can be calculated as follows:

$$\chi = \frac{\sigma}{\omega\epsilon_0} = 14.4$$

For simplicity, $\chi = 14.4$ can be ignored in comparison with $\epsilon_r = 75$; it can be concluded that:

$$\eta = \eta_0/\sqrt{75} = 0.0116\ \eta_0$$

$$R_H = R_V = \frac{\eta - \eta_0}{\eta + \eta_0}$$

3. The value of R_V and R_H for this case using Eqs. (3.59) and (3.60) is as follows:

$$R_H = -0.876, \quad R_V = -0.627$$

■

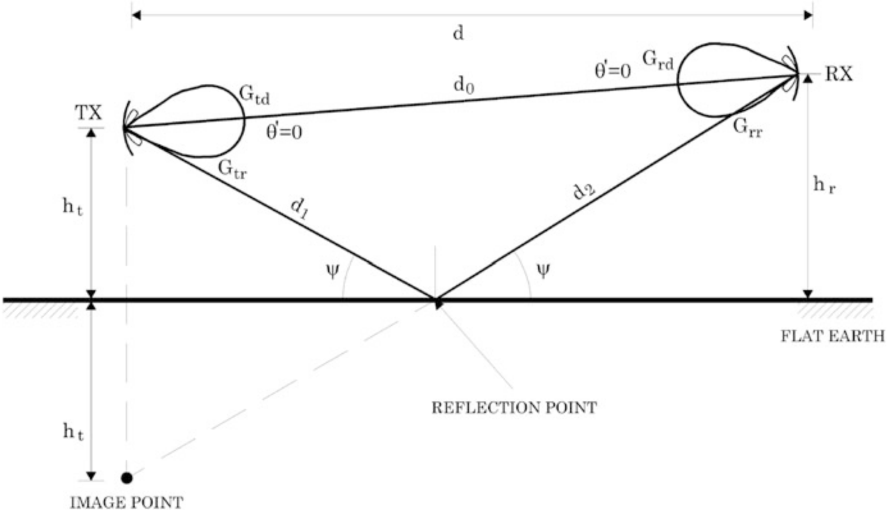

Fig. 3.18 Basic geometrical concept of multipath reception

3.6.2 Multipath Reception

Multipath phenomenon occurs when a radio-wave is received from different paths. The simplest case appears when the incident wave and the reflected wave from a flat surface are received simultaneously. The occurrence of this phenomenon is common in radio-communication, and its impact is considerable in various communication systems such as LOS microwave transmission, UHF radio, TV radio-waves, and radar systems.

According to Fig. 3.18, when the transmitter and receiver antennas are located in low heights above flat ground level, the simultaneous reception of incident and reflected waves can cause fading in the received signal.

When the surface is flat, the reflected signal can be modeled as a signal received from a virtual transmitter that is located at the symmetrical image point of real transmitter with respect to the ground surface. The main factors of multipath effect can be listed as follows:

- Reflection coefficient is almost -1 for both horizontal and vertical polarization if the grazing angle ψ approaches zero.
- Transmitter antenna gain denoted by G_{td} for LOS path and G_{tr} for reflection path, respectively.
- Receiver antenna gain denoted by G_{rd} for LOS path and by G_{rr} for reflection path, respectively.
- Distance difference between LOS path and reflection path denoted by Δd.
- Total field intensity at the receiver side which is the vector sum of incident and reflected waves is:

$$\begin{aligned}\bar{E}_t &= \bar{E}_d + \bar{E}_r \\ &= G_{td} \cdot G_{rd} \cdot \frac{e^{-jkd_0}}{4\pi d_0} + G_{rd} \cdot G_{rr} \cdot \frac{Re^{-jk(d_0+\Delta d)}}{4\pi d_0} \\ &= G_{td} \cdot G_{rd} \cdot \frac{e^{-jkd_0}}{4\pi d_0}\left[1 + R\frac{G_{rd} \cdot G_{rr}}{G_{td} \cdot G_{rd}} \cdot e^{-jk\Delta d}\right]\end{aligned} \tag{3.61}$$

The expression inside brackets is called path gain factor (PGF) and denoted by F with variation range from 0 to 2 ($0 \leq F \leq 2$).

- $F = 0$ means that the incident and reflected waves are out of phase and cancel each other perfectly.
- $F = 2$ means that the incident and reflected waves are in phase and reinforce each other perfectly.

By putting transmitter and receiver antennas at approximately the same height and close to ground level and setting their directions to be face to face (the normal situation in LOS transmission), in this case by using the Taylor series theorem and performing some simplifications and mathematical operations, the following results can be obtained:

$$d_0 = \sqrt{d^2 + (h_r - h_t)^2} \approx d + \frac{1}{2} \times \frac{(h_r - h_t)^2}{d} \tag{3.62}$$

$$d_1 + d_2 = \sqrt{d^2 + (h_r + h_t)^2} \approx d + \frac{1}{2} \times \frac{(h_r + h_t)^2}{d} \tag{3.63}$$

Combining the above two equations results in the following formula for distance difference:

$$\Delta d \approx \frac{2h_t \cdot h_r}{d} \tag{3.64}$$

$$\begin{aligned}|F| &= |1 - e^{2jkh_th_r/d}| = |e^{-jkh_th_r/d}(e^{+jkh_th_r/d} - e^{-jkh_th_r/d})| \\ &\Rightarrow \quad |F| = 2|\sin(kh_th_r/d)|\end{aligned} \tag{3.65}$$

The received power is directly proportional to the square of PGF according to the following expression:

$$P_r \propto |F|^2 = 4\sin^2\left(\frac{kh_th_r}{d}\right) \approx 4 \times \left(\frac{kh_th_r}{d}\right)^2 \tag{3.66}$$

It is obvious that the last approximation is based on the fact that $h_r.h_t \ll d$ and $R = -1$ which is often a realistic assumption.

Assuming that h_t is small in comparison to h_r, it results:

$$\tan\psi = \frac{h_r - h_t}{d} = \frac{\Delta h}{d} \approx \frac{h_r}{d} \tag{3.67}$$

In this case the equation for calculating $|F|$ is simplified to the following expression:

$$|F| = 2\,\sin(kh_t\,\tan\,\psi) \tag{3.68}$$

and its minimum and maximum values are:

$$\begin{aligned}
&\mathrm{Min}_{(\mathrm{PGF})}\;:\; kh_t\,\tan\psi = n\pi,\quad (n = 0, 1, \ldots)\\
&\frac{2\pi}{\lambda}h_t\,\tan\,\psi = n\pi \quad\Rightarrow\quad \tan\psi = \frac{n\lambda}{2h_t}\\
&\mathrm{Max}_{(\mathrm{PGF})}\;:\; kh_t\,\tan\psi = \frac{2n+1}{2}\pi,\quad (n = 0, 1, \ldots)\\
&\Rightarrow\quad \tan\psi = \frac{(2n+1)\lambda}{4h_t}
\end{aligned}$$

3.6.3 Coverage Diagram and Height Gain Curve

The graph of $|F|$ which its x and y axis represent the distance and the height of the receiver antenna, respectively, is called coverage diagram. In this graph, $|F|$ is in dB, h_r is in meter, and d is the distance normalized with respect to the base distance d_0. It is remarkable that if $d = d_0$, then it results in $E_t = E_d$ and consequently:

$$|F| = \left|2\left(\frac{d_0}{d}\right)\sin(kh_t\,\tan\,\psi)\right| \tag{3.69}$$

In some of “Radio Wave Propagation” books, the coverage diagrams are depicted for different sets of parameters. One example of these graphs is presented in Fig. 3.19.

Another approach to represent the received electrical field is path gain factor (PGF) diagram that shows received field intensity (PGF) changes in dB versus changes in d at a particular antenna height. An example of this diagram is presented in Fig. 3.20.

Evaluating PGF diagram indicates the following outstanding points:

- The maximum value points correspond to PGF = 2 that cause extra 6 dB increase in the gain of the received signal.
- The minimum value points correspond to PGF = 0 where the incident and reflected waves cancel each other completely.

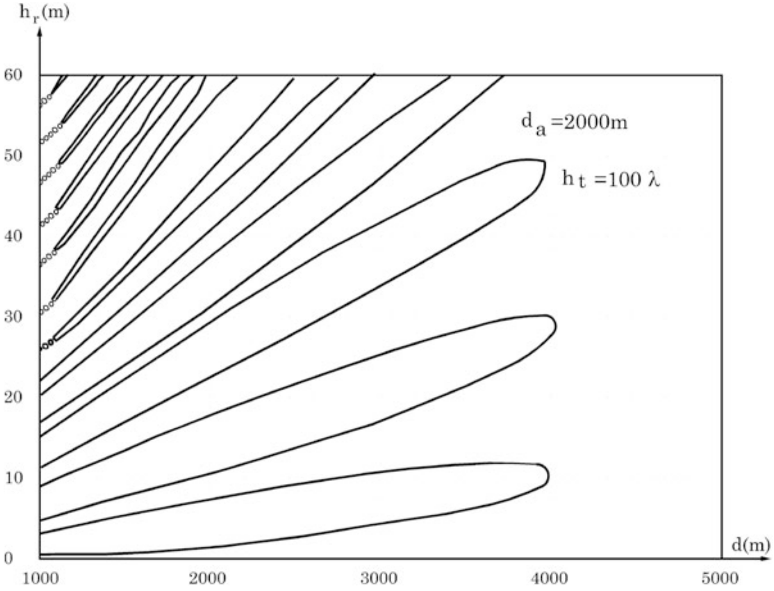

Fig. 3.19 Sample of coverage diagram

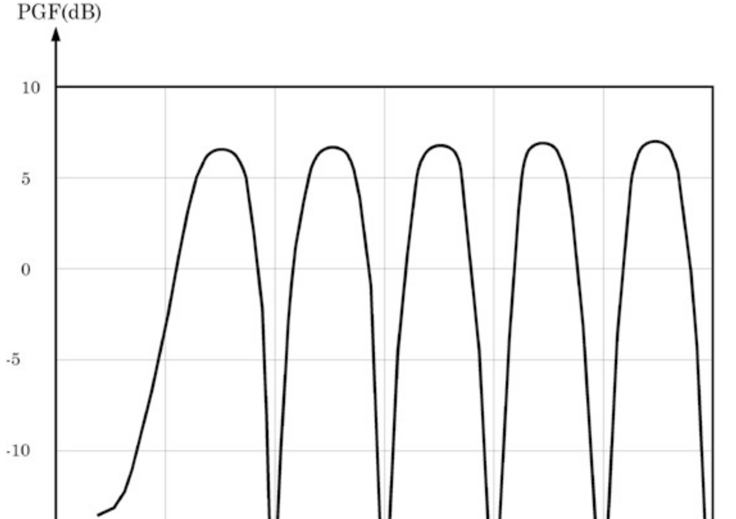

Fig. 3.20 Antenna height gain curve

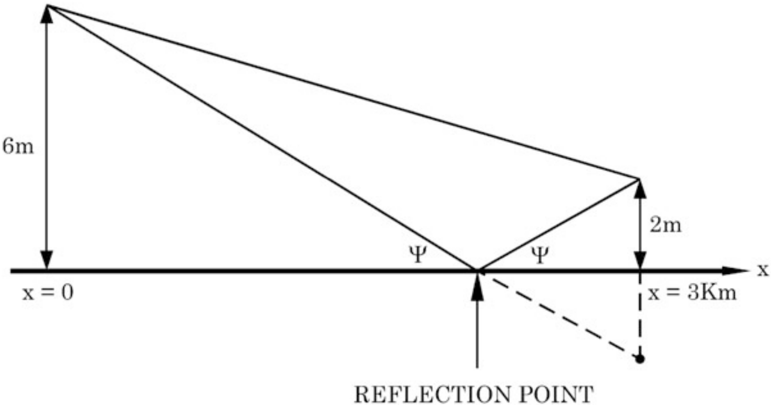

Fig. 3.21 Sketch for Example 3.10

- In practice the maximum and minimum positions may be subject to the change caused by several reflection paths.
- This approach is used to determine the appropriate height for receiving antennas in radio broadcasting systems.

Example 3.10. A radar antenna with 5 GHz frequency (in C-band) and 6 m height monitors the area of an airport. If there is an object 3 km away and 2 m above the ground, find:

1. Grazing angle
2. PGF value assuming $R = -1$
3. Decrease in received signal level with respect to the LOS signal.

Solution. 1. For the given situation, the ground can be assumed flat. So, according to Fig. 3.21, it can be concluded that:

$$\lambda = c/f \quad \Rightarrow \quad \lambda \; = \; 6\,\text{cm}$$

$$\tan\,\psi = \frac{6}{X_r} \; = \; \frac{2}{3 - X_r} \quad \Rightarrow \quad X_r \; = \; 2.25\,\text{km}$$

$$\psi = \tan^{-1}\left(\frac{6}{2250}\right) \quad \Rightarrow \quad \psi \; = \; 0.15^{\circ}$$

2. Based on Eq. (3.65):

$$|F| \; = \; \left|2\,\sin\left(\frac{kh_t h_r}{d}\right)\right| \; = \; 2\,\sin\frac{2\pi\times 6\times 2}{0.06\times 300} \; = \; 0.81$$

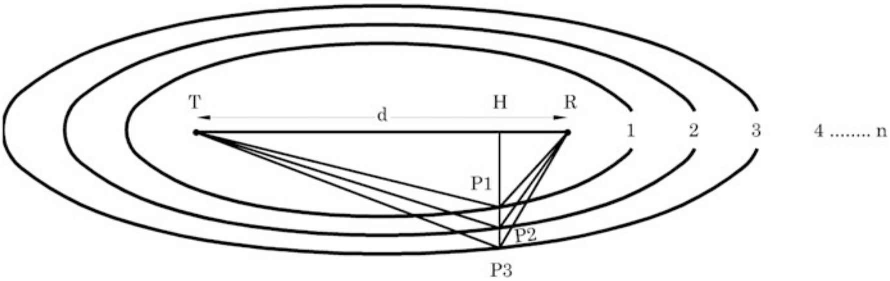

Fig. 3.22 Geometrical concept of Fresnel zones

3. The received signal level is directly proportional to $|F|^2$, so the loss ratio (LR) can be written as:

$$\mathrm{LR} = 20\log|F| \quad \Rightarrow \quad \mathrm{LR} = -1.83\,\mathrm{dB}$$

■

3.6.4 Fresnel Zones

To define Fresnel zones, Fig. 3.22 is used. As shown in this figure, the transmitter antenna location is presented by T, the receiver antenna location is presented by R, and the main signal path is assumed to be $TR = d$.

In this case, if P_1 is a point where the sum of its distances from points T and R is greater than d and equals to half a wavelength, it means that:

$$P_1T + P_1R = d + \frac{\lambda}{2} \tag{3.70}$$

The locus of these points forms ellipse No. 1 and in three-dimensional space will be converted to an ellipsoid surface, and the geometrical position of P1 forms a circle centered at H with radius equal to P_1H. According to the definition, $r_1 = P_1H$ and it is called the radius of first Fresnel zone at point P. Similarly the loci of points P_2 are the sum of their distances from points T and R greater than d and equal to two times of half a wavelength, forming ellipse No. 2, and the loci of points P_3 are the sum of their distances from points T and R greater than d and equal to three times of half a wavelength, forming ellipse No. 3, and so on. As a general rule, the loci of points P_n are the sum of their distances from points T and R greater than d and equal to n times of half a wavelength as shown by Eq. (3.76), forming ellipse number n in a way that:

$$P_nT + P_nR = d + n \cdot \frac{\lambda}{2} \tag{3.71}$$

In a three-dimensional space, the geometrical positions of points P_n that form ellipsoid surfaces are called nth Fresnel zone and their radius at point H of the path is equal to:

$r_1 = P_1 H$: Radius of first Fresnel zone in point P_1

$r_2 = P_2 H$: Radius of second Fresnel zone in point P_2

.

.

.

$r_n = P_n H$: Radius of nth Fresnel zone in point P_n

According to Fig. 3.22, Fresnel radius depends on the following factors:

- Path length between transmitter and receiver denoted by d.
- Position of point H, or the length of d_1 and d_2.
- Wavelength λ.
- Number of Fresnel zone denoted by n

3.6.5 Fresnel Radius Calculation

In order to calculate the radius of nth Fresnel zone according to Fig. 3.23, the following conditions should be fulfilled:

$$\Delta d = (l_1 + l_2) - (d_1 + d_2) = n\frac{\lambda}{2} \tag{3.72}$$

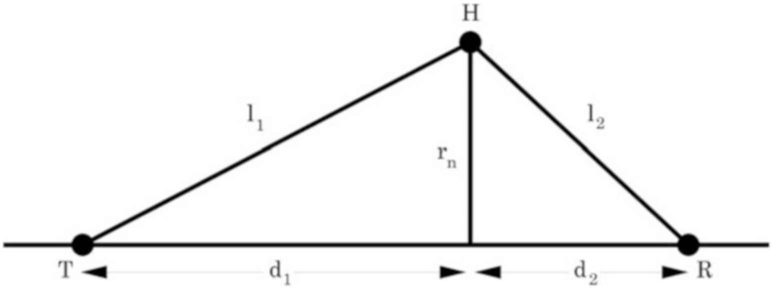

Fig. 3.23 Radius of nth Fresnel zone

$$l_1 = \sqrt{r_n^2 + d_1^2} \quad \Rightarrow \quad l_1 \approx d_1\left[1 + \frac{1}{2}\left(\frac{r_n}{d_1}\right)^2 + \cdots\right] \tag{3.73}$$

$$l_2 = \sqrt{r_n^2 + d_2^2} \quad \Rightarrow \quad l_2 \approx d_2\left[1 + \frac{1}{2}\left(\frac{r_n}{d_2}\right)^2 + \cdots\right] \tag{3.74}$$

Taking into account that in practical LOS links r_n is normally too small in comparison with d_1 and d_2, and ignoring the higher-order terms of series of the last two equations, the following equation is obtained:

$$r_n = \sqrt{n \times \frac{d_1 d_2}{d_1 + d_2} \times \lambda} \tag{3.75}$$

Consequently, the radius of first Fresnel zone which is very important is:

$$r_1 = \sqrt{\frac{d_1 d_2}{d_1 + d_2} \times \lambda} \tag{3.76}$$

Similarly, the radius of nth Fresnel zone can be calculated simply by the following equation:

$$r_n = r_1\sqrt{n} \tag{3.77}$$

It is notable that although the distance between points T and R usually is not straight and horizontal, the mentioned equations are valid and acceptable for most of practical cases.

The radius of Fresnel zone is important in LOS microwave transmission in the sense that if point P_1 is assumed the reflection point with reflection coefficient equal to -1, then the phase difference between the incident and reflected waves in the path between points R and T is 360°, in other words the main and reflected signals on the receiver are in phase. This is because of 180° due to reflection and 180° due to path length difference equal to $\lambda/2$. So, the received signal level at the receiver is even greater than when there is only the LOS reception.

Similarly, if point P2 is assumed the reflection point with reflection coefficient equal to -1, then the phase difference between incident and reflected waves is $360° + 180°$; therefore, they are out of phase signals and attenuate each other sharply.

Finally, the Fresnel zones of surfaces with odd numbers (1,3,5,...) form the geometrical positions of points, and their reflected waves are in phase with incident waves and reinforce each other, while the ellipsoid surfaces with even numbers (2,4,6,...) form the geometrical positions of points and their reflected waves have opposite phase with respect to incident waves and attenuate each other.

In addition to reflection phenomenon, some other items such as refraction phenomenon, attenuation of obstacles, and LOS criterion of wave path clearance can

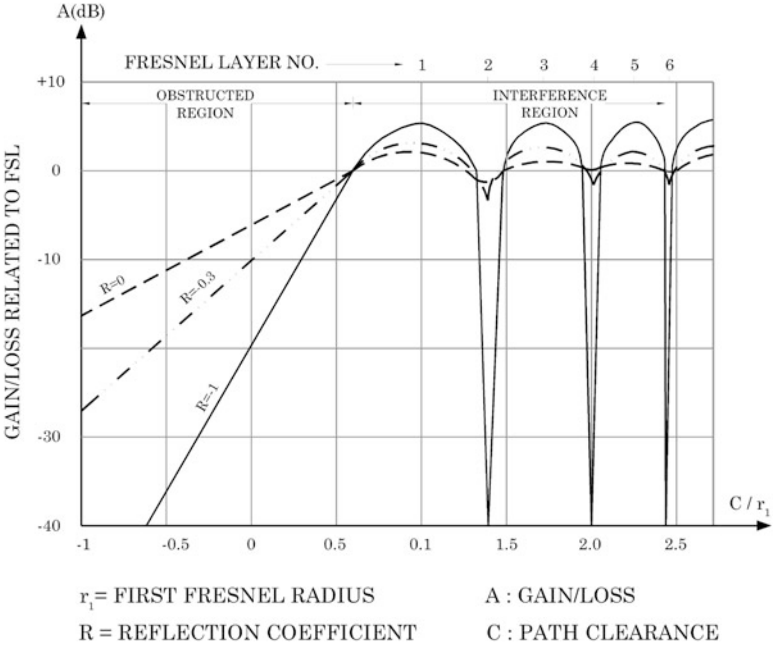

Fig. 3.24 Radiowave gain/loss vs. path clearance

be described and calculated based on Fresnel zone radius. In Fig. 3.24, the amount of increase and decrease in main signal level caused by reflected waves and obstacle attenuation is determined for three different values of reflection coefficients. It is remarkable that the reflection coefficients of knife-edge obstacles are 0, while it is assumed about −0.3 for ordinary obstacles and −1 for smooth obstacles such as salty sea-water surface.

Example 3.11. In a 25 km point to multi point (P-MP) communication link at 2.4 GHz frequency band, find:

1. The radius of first and forth Fresnel zones at the distance of 10 km from the transmitter.
2. The equation of locus of points in the plane and sum of their distances from transmitter and receiver is a half wavelength greater than LOS distance between transmitter and receiver.
3. The radius of first and forth Fresnel zones at the middle of transmission path.

Solution. 1.

$$\lambda = 12.5\,\text{cm}, \quad d_1 = 10\,\text{km}, \quad d_2 = 15\,\text{km}$$

$$r_1 = \sqrt{\frac{10 \times 15}{25} \times 10^3 \times 0.125} \quad \Rightarrow \quad r_1 = 27.39\,\text{m}$$

$$r_4 = r_1 \times \sqrt{n} \quad \Rightarrow \quad r_4 = 54.78$$

2. The locus is an ellipse with focal points at R and T and the following parameters:

$$2c = 25\,\mathrm{km}, \quad 2a = 25 + \lambda/2$$
$$2b \approx 5\sqrt{\lambda}, \quad \lambda = 1.25 \times 10^{-4}\,\mathrm{km}$$

3. The radii of first and fourth ellipses at the middle of transmission line are:

$$R_1 = \sqrt{\frac{12.5 \times 12.5}{25} \times 10^3 \times 0.125} = 27.95\,\mathrm{m}$$
$$R_4 = R_1 \times \sqrt{n} \quad \Rightarrow \quad R_4 = 55.9\,\mathrm{m}$$

■

3.7 Radiowave Diffraction

3.7.1 Introduction

Diffraction phenomenon initially was studied and discovered for visible light-waves, and because of the same nature of light- and radio-waves and based on the fact that both follow electromagnetic laws, thus, diffraction mechanism is used in several types of radio-communications including mobile radio systems.

In this section, the diffraction phenomenon is investigated theoretically and its equations are stated. Also, reader is referred to Chap. 6 that deals with radiowave propagation in VHF/UHF band in detail and provides its rules, equations, and applications.

Diffraction occurs when radiowave encounters an obstacle according to Fig. 3.25, and it radiates in different directions beyond geometrical principles of light. Therefore, part of the wave energy penetrates into the dark and invisible region. In some cases the amount of this energy is considerable and can be detected by receivers which may be used in wireless radio systems and also radio broadcasting at VHF and UHF bands.

It is worthy to note that the field intensity not only in shadow zone but also in visible part around tangent ray is affected by this phenomenon.

Considering Fig. 3.25, the main factors of diffraction are defined as follows:

- Extension of line TD is called boundary line (or tangent ray) and above it is considered visible zone and bellow it is considered as invisible or shadow zone.
- Angle between boundary line and DR line is called deviation angle and is denoted by α.

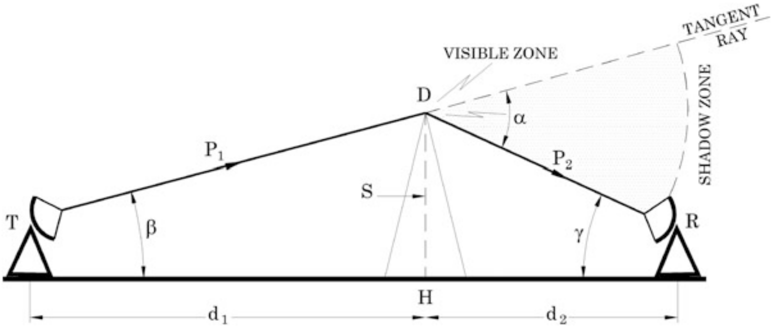

Fig. 3.25 Radiowave diffraction concept

- Phase difference between virtual straight path TR and the actual path TDR denoted by ϕ.
- Length difference between actual path length $(P_1 + P_2)$ and virtual path length $(d_1 + d_2)$ denoted by $\varDelta$.

3.7.2 Diffraction Parameter

Diffraction parameter denoted by V is defined as a function of the following factors:

- Deviation angle a
- Distance between transmitter and receiver
- Wavelength

According to Fig. 3.25, the following equations can be derived:

$$P_1 = \sqrt{d_1^2 + S^2} \quad \Rightarrow \quad P_1 = d_1 + \frac{S^2}{2d_1} \tag{3.78}$$

$$P_2 = \sqrt{d_2^2 + S^2} \quad \Rightarrow \quad P_2 = d_2 + \frac{S^2}{2d_2} \tag{3.79}$$

$$\varDelta = (P_1 + P_2) - (d_1 + d_2) \tag{3.80}$$

$$\varDelta = \frac{S^2}{2}\left(\frac{d_1 + d_2}{d_1 d_2}\right) \tag{3.81}$$

$$\phi = 2\pi \times \frac{\varDelta}{\lambda} = \frac{\pi}{2}\left[\frac{2(d_1 + d_2)}{\lambda d_1 d_2}\right] S^2 = \frac{\pi}{2} V^2 \tag{3.82}$$

$$S \ll d_1, d_2 \quad \Rightarrow \quad a = \beta + \gamma = \frac{S}{d_1} + \frac{S}{d_2} = S \cdot \frac{d_1 + d_2}{d_1 d_2} \tag{3.83}$$

Applying the above items, the following formulas are obtained:

$$S = a\frac{d_1 d_2}{d_1 + d_2} \tag{3.84}$$

$$\phi = \frac{\pi a^2}{\lambda}.\frac{d_1 d_2}{d_1 + d_2}\ (\text{rad}) \tag{3.85}$$

$$V = a\sqrt{\frac{2d_1 d_2}{(d_1 + d_2)\lambda}} = S\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \tag{3.86}$$

3.7.3 Field in Diffraction Region

There is not a straight-forward and simple approach to calculate the field intensity in diffraction region around the boundary line, but if the obstacle is smooth and the receiver point is located deep enough in the shadow (invisible) region, the following simple equation can be used to calculate the field:

$$F = V(X) \cdot U(Z_1) \cdot U(Z_2) \tag{3.87}$$

In the above equation, the main factor of attenuation is the function $V(X)$ with the analytical closed form equation. Its value can also be obtained from Fig. 3.26.

$$V(X) = 2\sqrt{\pi X} \cdot e^{-2.02X} \tag{3.88}$$

For functions $U(z_1)$ and $U(z_2)$, the graph presented in Fig. 3.27 is used. In the mentioned curves and equations, the arguments are as follows:

X: Distance factor
Z: Antenna height factor (Z_1 for the transmitter antenna and Z_2 for the receiver antenna)

First, the length (L) and height (H) parameters should be calculated for each particular case, using the following expressions.

$$L = 2\left(\frac{(R_e')^2}{4K_0}\right)^{1/3} \tag{3.89}$$

$$H = 2\left(\frac{R_e'}{2K_0^2}\right)^{1/3} \tag{3.90}$$

In the above equations, R_e' is the effective Earth radius and $K_0 = 2\pi/\lambda$ is the wave number. For the standard case when the factor K is equal to 4/3, the above equations are simplified to:

$$L = 28.41\lambda^{1/3}\ [\text{km}], \quad H = 47.55\ \lambda^{2/3}\ [\text{m}] \tag{3.91}$$

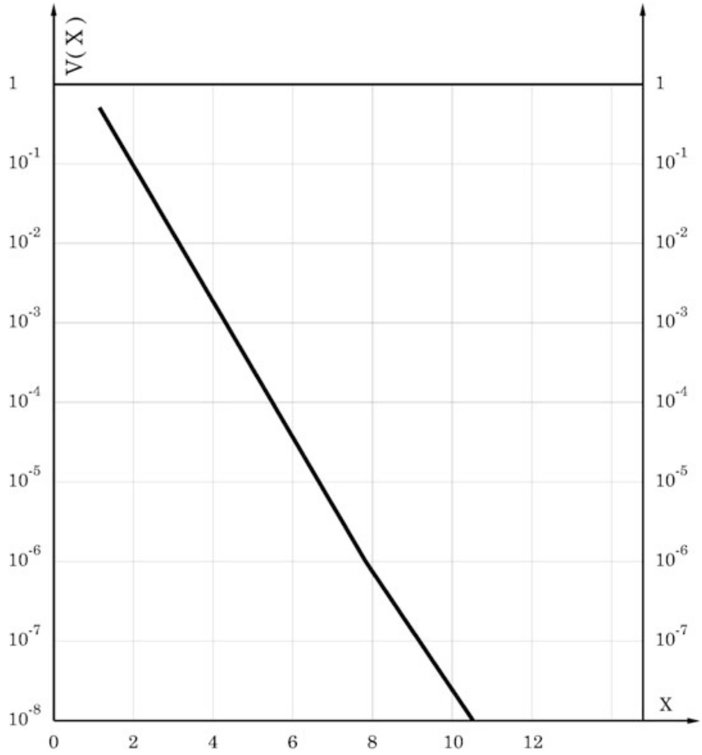

Fig. 3.26 Distance loss function, $V(X)$

In the last equations, λ is in meter. For the mentioned assumptions, the values of X and Z can be calculated based on the distance and antenna heights according to the following equations:

$$X = \frac{d}{L}, \quad Z_1 = \frac{h_1}{H}, \quad Z_2 = \frac{h_2}{H} \tag{3.92}$$

3.7.4 Field in Interference Region

The equations developed for multipath propagation in Sect. 3.6.2 can be used to calculate the field intensity in the interference region. The only extra issue is to consider the ray divergence mechanism due to reflection which causes attenuation in reflected waves at the receiver location, and therefore using Eq. (3.65), the path gain F is changed to the following expression by noting reflection coefficient ρ and phase ϕ:

$$F = |1 + D\rho\, e^{j\phi - jK_0 \Delta R}| \tag{3.93}$$

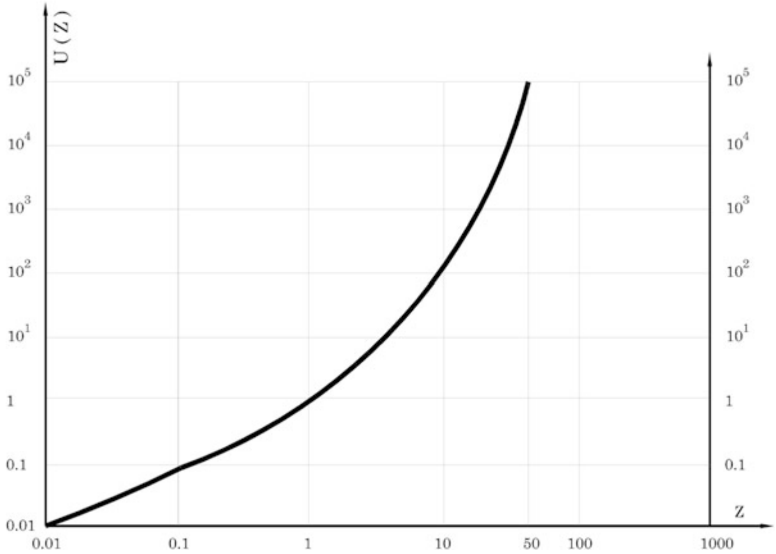

Fig. 3.27 Antenna height gain function

Applying further mathematical operations and simplification, the above equation converts to:

$$F = \left[(1 + D\rho)^2 - 4D\rho \ \sin^2 \left(\frac{\phi - k_0 \Delta R}{2} \right) \right]^{1/2} \tag{3.94}$$

Assuming that the reflection coefficient for flat ground surface is ($\phi = 180°$, $\rho = 1$), it results in:

$$F = \left[(1 + D)^2 - 4D \ \cos^2 \left(\frac{k_0 \Delta R}{2} \right) \right]^{1/2} \tag{3.95}$$

$$= \left[(1 + D)^2 - 4D \ \cos^2 \left(\frac{\pi}{2} \zeta \right) \right]^{1/2}$$

The following equations can be used in order to calculate D for smooth surfaces as stated in electromagnetic reference books:

$$D = \left[1 + \frac{4 \, S_1 \cdot S_2^2 \cdot T}{S(1 - S_2^2)(1 + T)} \right]^{-1} \tag{3.96}$$

$$S_1 = \frac{d_1}{\sqrt{2R'_e \cdot h_1}}, \quad S_2 = \frac{d_2}{\sqrt{2R'_e \cdot h_2}} \tag{3.97}$$

In Eqs. (3.96) and (3.97), it should be considered that h_1 is the smaller antenna height, and therefore h_2 is the higher one (for TX and RX antennas).

$$S = \frac{d}{\sqrt{2R'_e \cdot h_1} + \sqrt{2R'_e \cdot h_2}} = \frac{d}{d_{\mathrm{RH}}} = \frac{S_1 T + S_2}{1 + T} \tag{3.98}$$

$$T = \sqrt{\frac{h_1}{h_2}} \quad (h_1 < h_2 \quad \Rightarrow \quad T < 1) \tag{3.99}$$

Also, the following equations can be used to calculate the reflection point with distances d_1 and d_2 measured from two end points of transmission path.

$$d_1 = \frac{d}{2} + P \cos\left(\frac{\phi + \pi}{3}\right), \quad d_2 = d - d_1 \tag{3.100}$$

$$\phi = \cos^{-1}\left[\frac{2R'_e(h_1 - h_2)d}{P^3}\right] \tag{3.101}$$

$$P = \frac{2}{\sqrt{3}}\left[R'_e(h_1 + h_2) + \frac{d^2}{4}\right]^{1/2} \tag{3.102}$$

There is also another methodology which is developed in some other books as follows:

$$k_0 \Delta R = \frac{2kh_1h_2}{d}(1 - S_1^2)(1 - S_2^2) = \gamma\zeta\pi \tag{3.103}$$

$$\gamma = \frac{4h_1^{3/2}}{\lambda\sqrt{2R'_e}} = \frac{h_1^{3/2}}{1030\lambda} \tag{3.104}$$

$$\zeta = \frac{h_2/h_1}{d/d_T}(1 - S_1^2)(1 - S_2^2) \tag{3.105}$$

$$d_T = \sqrt{2R'_e h} \tag{3.106}$$

3.7.5 Field in the Midpath Region

There is no simple approach to calculate the field intensity in the midpath region as stated before. It can be obtained by using graphs and applying interpolation with acceptable accuracy. To do so, the value of F is calculated for two or more points in the invisible region (shadow zone) based on the approach developed in Sect. 3.7.3 and also for two or more points in the interference region and according to the approach stated in Sect. 3.7.4, a curve is plotted with these points giving F versus distance for a particular case. This approach can be summarized with the following steps:

Step 1: Choose two or more points in the invisible region, for instance, $d_1 = 2d_T,\ d_2 = 3d_T$ and calculate F for these points.

Step 2: Choose two or more points in the interference region and calculate F for these points.

Step 3: Plot the 20 log F curve versus normalized distance d/d_T using curve fitting and interpolation methods.

Step 4: Find 20 log F for desired point with the given normalized distance in the midpath region.

Example 3.12. In a microwave hop, the heights of transmitter and receiver antennas are 30 m and 20 m, respectively. For the frequency of 10 GHz, the standard propagation condition and the following parameters:

$$d = d_T \qquad d = 1.1 d_T$$
$$\gamma\zeta = 1, \quad \gamma\zeta = 0.5$$
$$D = 0.75 \qquad D = 0.6$$

1. Find the effective receiver path gain F.
2. Plot F curve versus normalized distance for the given hop.
3. Calculate the received signal power for antennas with $G_t = 40\,\mathrm{dB}_i$ and $G_r = 38\,\mathrm{dB}_i$ gains and transmission power equal to 500 mW at a distance equal to 30 km.

Solution. 1. L and H parameters and radar horizon for standard situation can be calculated using (3.91):

$$L = 13.2\,\mathrm{km}, \quad H = 10.24\,\mathrm{m}$$
$$d_T = \sqrt{2R'_e \cdot h_t} = 4.12\sqrt{h_t} \;=\; 22.52\,\mathrm{km}$$

Then, the arguments X and Z are obtained using Eq. (3.92), and finally F is calculated:

$$X = \frac{3d_T}{L} = 5.12 \quad \Rightarrow (\text{Fig. 3.26}) \Rightarrow \quad 20\log V(X) = -70\,\mathrm{dB}$$
$$Z_1 = \frac{h_1}{H} = 2.93 \quad \Rightarrow (\text{Fig. 3.27}) \Rightarrow \quad 20\log U(Z_1) = 19\,\mathrm{dB}$$
$$Z_2 = \frac{h_2}{H} = 1.95 \quad \Rightarrow (\text{Fig. 3.27}) \Rightarrow \quad 20\log U(Z_2) = 13\,\mathrm{dB}$$

$$20\log F = 20\log V(X) + 20\log U(Z_1) + 20\log U(Z_2)$$
$$\log F = -1.9, \quad F = 0.0126$$

2. The following steps should be done to plot F curve:
   - **Step 1:** F value is found in the dark region for $d = 3d_T$:

$$d = 3d_T \quad \Rightarrow \quad 20 \log F = -38\,\text{dB}$$

Also, F is calculated for $d = 2d_T$:

$$X = 3.41, \quad Z_1 = 2.93, \quad Z_2 = 1.95$$
$$20 \log V(X) = -47, \quad 20 \log U(Z_1) = 19, \quad 20 \log U(Z_2) = 13$$
$$\Rightarrow \quad 20 \log F = -1\,\text{dB}, \quad d = 2d_T$$

- **Step 2:** Using Eq. (3.95), the following results are obtained:

$$d = 2d_T \quad \Rightarrow \quad F = 1 + D = 1.75 \quad \Rightarrow \quad 20 \log F = 4.86\,\text{dB}$$
$$d = 1.1\ d_T \quad \Rightarrow \quad F = \sqrt{1 + D^2} = 1.166 \quad \Rightarrow \quad 20 \log F = 1.334\ \text{dB}$$

- **Step 3:** Figure 3.28 is plotted based on the calculated results:

3. Taking into account that $d_T = 22.5$ for this example, $d/d_T = 1.33$ and according to the graph, it is clear that $20 \log F = -3\,\text{dB}$ and $F = 0.7$. So, applying the following equations results in:

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi d)^2} \times F^2$$
$$10 \log P_r = 10 \log P_t + G_t + G_r + 20 \log \lambda + 20 \log F - 10 \log(4\pi d^2)$$
$$P_r[\text{dB}_m] = P_t[\text{dB}_m] + G_t + G_r - 34 + 20 \log F - 10 \log(4\pi d^2)$$
$$P_r[\text{dB}_m] = 30 + 40 + 40 - 34 + (-3) - 100.5 = -27.5\,\text{dB}_m$$

■

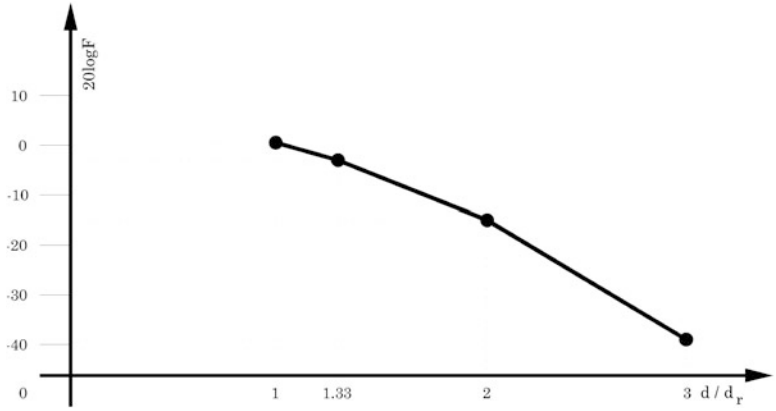

Fig. 3.28 Path gain F for Example 3.12

3.8 Attenuation of Obstacles

Generally, when there is an obstacle in the direct path between the transmitter and the receiver, the radiowave can be detected at the receiver by the following two approaches:

- Passing through the obstacles and suffering related attenuation.
- Using diffraction mechanism in a way that the waves encounter obstacle edges and penetrate to the dark region behind the obstacle.

Both of the above-mentioned options have their own applications in particular conditions. When the beam width of transmitter antenna is wide as in sectoral or isotropic antennas, for a specific application (such as wireless communication and broadcasting systems), the diffraction phenomenon is the dominant one because of the following reasons:

- Identical power transmission for different paths including straight and diffracted paths
- High loss for straight LOS path because of high thickness of natural obstacles in comparison with the wavelength

In LOS transmission such as point-to-point or point-to-multi-point links in UHF/SHF bands and radar transmission, due to the usage of directional antennas at high frequencies, diffraction mechanism is not applicable, and taking into account the obstruction loss is a better approach just for the case that the obstacle thickness is not too high in comparison with wave penetration depth.

3.8.1 *Obstruction Loss in Diffraction Condition*

Obstruction loss in diffraction condition stated in Sect. 3.7 will be discussed in Chap. 6, particularly concerning VHF/UHF in point-to-area radio-communications. In this section, the following simple and practical methods are summarized.

3.8.1.1 Knife-Edge Obstacles

The following empirical formula indicates the relation between field intensity E and the radiated power EIRP of an obstructed radio link of length d, where L_{ke} is the knife-edge obstacle attenuation:

$$E[\text{dB}] = 104.8 + 10\ \log\ \text{EIRP}[\text{kW}] - 20\ \log\ d[\text{km}] - L_{\text{ke}}[\text{dB}] \tag{3.107}$$

In the above formula, L_{ke} is the attenuation of knife-edge obstacle and can be obtained for different values of diffraction parameter (V) from Table 3.4.

Table 3.4 Knife edge attenuation vs. diffraction parameter

V	0	1	2	3	4	5	10	20
L_{ke} [dB]	6	13	19	22	25	27	33	39

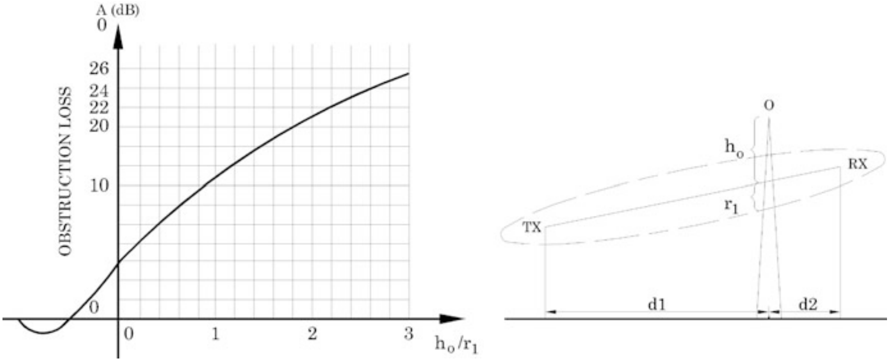

Fig. 3.29 Knife edge attenuation vs. obstruction relative height

In addition to the mentioned procedure, there is another approach to calculate the attenuation of knife-edge obstacle based on the graph depicted in Fig. 3.29.

In this approach, the attenuation value A_0 is obtained based on the ratio of obstacle height to the first Fresnel zone radius. The presented curve is valid for $\frac{h_0}{r_1} < 3$. The following formula can be used for $\frac{h_0}{r_1} \geq 3$ with acceptable accuracy.

$$L_{ke}[\text{dB}] = 16 + 20\ \log\left(\frac{h_0}{r_1}\right) \tag{3.108}$$

In this formula, h_0 is the height of obstacle on the ray path, and r_1 is the radius of the first Fresnel zone at the location of obstacle, and both should have the same unit.

3.8.1.2 Rounded or Smooth Obstacle

In order to calculate the attenuation caused by rounded or smooth obstacles, the extra loss according to the following equation should be considered in addition to L_{ke}:

$$L_{ex} = 11.7 \times \sqrt{\left(\pi \frac{R}{\lambda}\right)}\ (\text{dB}) \tag{3.109}$$

where the parameters and their units are:

- R is the average radius of rounded obstacle in meter

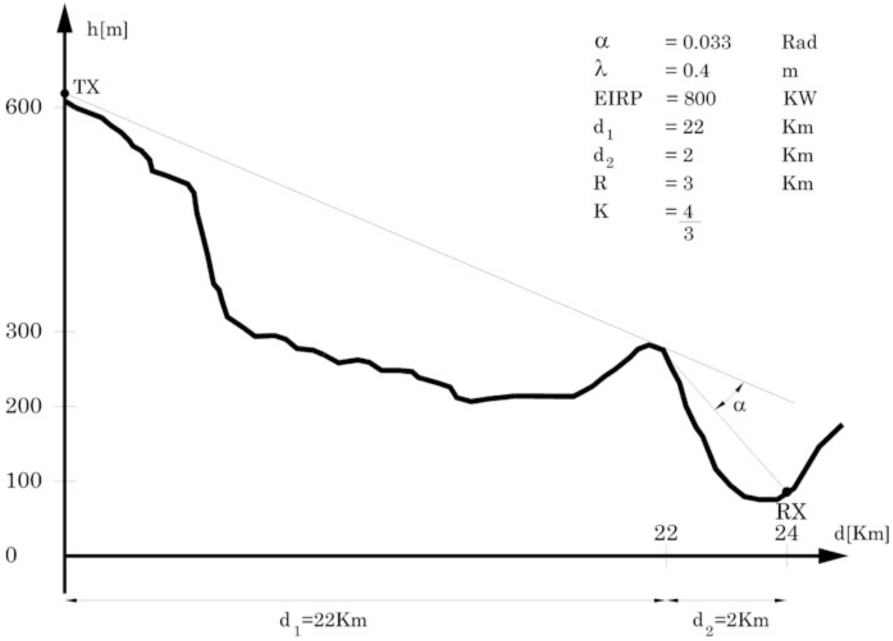

Fig. 3.30 Sketch for Example 3.13

- λ is the wavelength in meter
- L_{ex} is additional attenuation caused by the rounded obstacle in dB

Equation (3.109) is valid for smooth obstacles in mountainous areas and buildings as well as forests. The following equation can be used for areas without buildings and trees:

$$L_{ex} = 7.5 \times \sqrt{\pi \frac{R}{\lambda}} \text{ (dB)} \tag{3.110}$$

Example 3.13. According to Fig. 3.30 and the following data for a TV transmitter and receiver system:

1. Find the electric field intensity at the receiver location.
2. If the sensitivity of receiver is $70\,\mathrm{dB}_{\mu V/m}$, verify whether the received signal is detectable or not?
3. Which solution can be proposed to receive the signal properly?

Solution. 1. The signal level without considering the obstacle is:

$$E = 104.8 + 10 \log 800 - 20 \log 24 = 106\,\mathrm{dB}_{\mu V}$$

To calculate the loss of smooth obstacle, first, the knife-edge obstacle attenuation should be calculated and then additional loss term be added.

$$V = a\sqrt{\frac{2d_1 d_2}{(d_1 + d_2)\lambda}} = 0.03\sqrt{\frac{2 \times 22 \times 2}{24 \times 0.4 \times 10^{-3}}} = 3.16$$

$$V = 3.16 \rightarrow \text{Table } 2.2 \rightarrow L_{\text{ke}} = 23\,\text{dB}$$

$$L_{\text{ex}} = 7.5 \times \left(\pi \frac{R}{\lambda}\right)^{\frac{1}{2}} = 38\,\text{dB}$$

$$E_r = 45\,\text{dB}_{\mu\text{V/m}}$$

E_r value can be converted to V/m unit using the following equation.

$$20 \log E_r(\text{dB}_{\mu\text{V/m}}) = 45 \quad \Rightarrow \quad E_r = 177.8\,\mu\,\text{V/m} = 1.78 \times 10^{-4}\,\text{V/m}$$

2. Since the received signal level is less than the sensitivity level of TV receivers, so it is not detectable by TV receivers.
3. The following modifications can be done in order to increase the received signal level for the fixed transmitter parameters.

    - Increasing the receiver antenna height which results in the reduction of the angle a, and consequently it causes reduction in the loss values L_{ex} and L_{ke}
    - Using directional antennas (yagi types or similar antennas) that increase the signal level at the receiver due to higher gains. ■

3.8.2 Obstructed Radio Path

Sometimes radiowaves encounter obstructions such that the diffraction theory cannot be used, for instance when there is a wall with thickness of d in radio path. For similar cases the following procedure can be used to calculate received signal level:

step 1: Fix the obstruction thickness d and frequency f
step 2: Calculate radiowave penetration depth δ
step 3: Calculate obstruction loss L_O using the following formula

$$L_O[\text{dB}] = 6 \times \frac{d[\text{m}]}{\delta[\text{m}]} \tag{3.111}$$

step 4: Calculate the received signal level applying link power budget relation for transmitter power, receiver sensitivity, free-space loss, antenna gain, and miscellaneous losses.

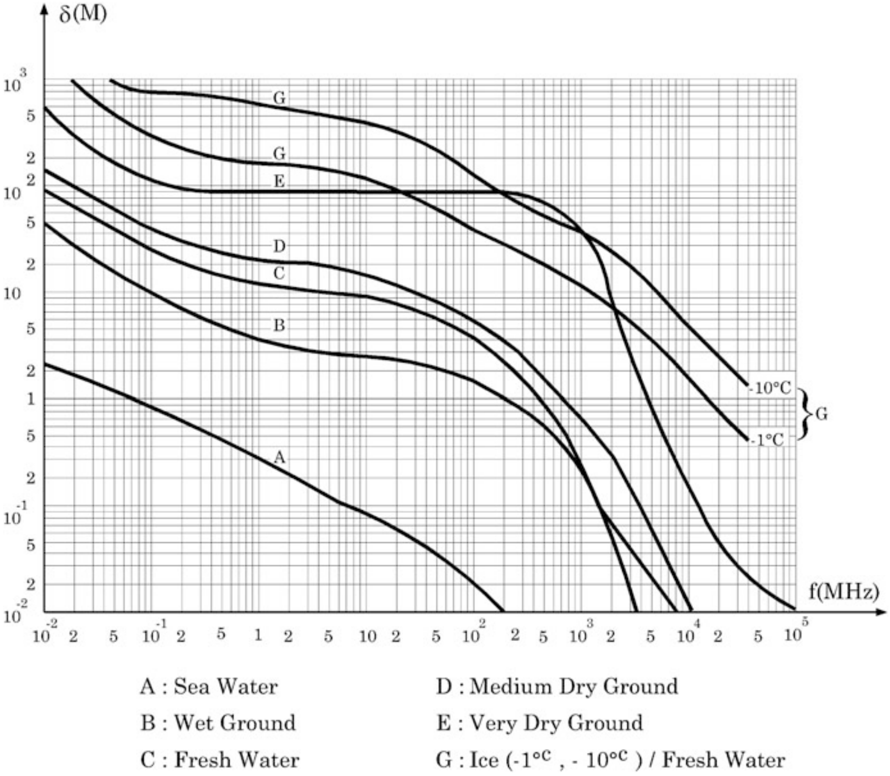

Fig. 3.31 Variations of penetration depth vs. frequency

The graph of radiowave penetration depth versus frequency for different environments based on ITU-R recommendations is depicted in Fig. 3.31. As shown in the graph, the penetration depth depends on the frequency in addition to the material of obstacle and decreases rapidly with the frequency.

3.9 Forest and Vegetation Area

3.9.1 Overall Views

In some cases, radiocommunications are required in forests, vegetation, and green areas where radiowaves encounter trees and plants in their propagation path. These cases occur often for wireless networks and point-to-area systems, so characteristics and impacts of this kind of obstructions on the propagating radiowaves should be identified clearly and considered carefully for applying the effects and limitations on radio system design.

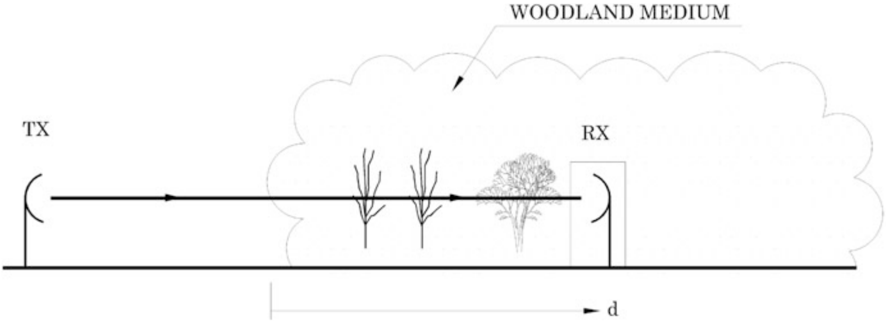

Fig. 3.32 Basic concept of radio link in vegetation and forest areas

Based on the above introduction, some worldwide studies and researches have been conducted in this field by communication engineers and researchers, and summary of their results is presented in this section. In general, the loss of vegetation coverage and forests is considerable in terrestrial and satellite communications, and especially its effects are significant for point-to-area wireless systems. This section is prepared mostly based on ITU-R recommendations specially P.833.

It is challenging and very difficult to provide a closed form equation and straightforward solution to this problem because of their complicated conditions. So, some solutions and equations are provided based on practical measurements and field experiments that are very useful and applicable. In terrestrial communications, when a radio station is located in the forest area, a garden or a park full of trees and plants, the radiowave suffers excess attenuation in addition to the losses stated before. This type of loss depends on the following factors:

- Vegetation specific loss index in dB/m that appears mainly because of scattering of the energy of radiowaves when they pass through or encounter an area covered with trees and plants.
- Maximum vegetation loss denoted by A_m in dB that gives an upper limit for losses caused by other mechanisms in signal path through forest, jungles, and woodlands.

As shown in Fig. 3.32, the excess loss caused by trees and plants, denoted by $A_{e\gamma}$, can be obtained from the following equation:

$$A_{e\gamma} = A_m[1 - e^{-\gamma d/A_m}] \text{ (dB)} \tag{3.112}$$

In the above equation, the parameters and their units are defined as follows:

- d: Length of the radio link inside vegetation and plants in m
- γ: Specific loss index for short paths in dB/m
- A_m: Maximum loss value for a radio link in a forest or vegetation area

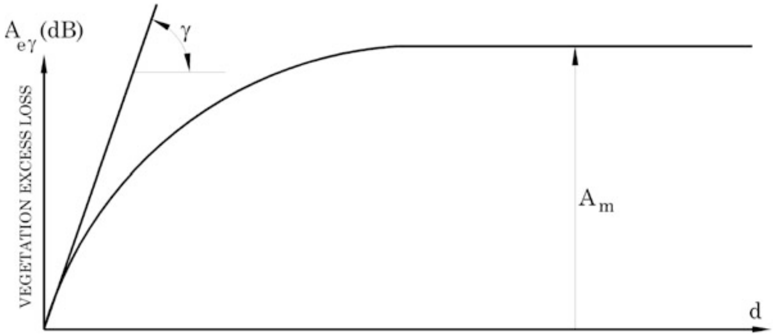

Fig. 3.33 Excess loss of vegetation and forest areas

It is notable that $A_{e\gamma}$ is an extra attenuation in addition to the other types of losses based on different mechanisms such as free-space loss. For instance, according to Fig. 3.33, it should be noted that:

- If the path structure is such that the open path criteria are not fulfilled by the equivalent radius of the first Fresnel zone, then $A_{e\gamma}$ is an extra loss in addition to the sum of free-space and diffraction losses.
- In high frequencies (higher than 10 GHz), where atmospheric gas absorption occurs, $A_{e\gamma}$ is an extra loss in addition to the sum of free-space, diffraction, and atmospheric absorption losses.
- A_m is the clutter loss that is mainly defined for radio base stations blocked by ground cover or clutters.

3.9.2 VHF/UHF Frequency Bands

The specific loss index for trees depends on the type, structure, and density of trees in the area, and an approximation of its value for the common case is depicted as a function of frequency in Fig. 3.34. This graph is provided based on practical measurement results provided under ITU-R recommendation P.833 for horizontally and vertically polarized waves at VHF and UHF frequency bands.

As shown in Fig. 3.34 at frequencies less than 1 GHz, the specific index for vertical polarization is greater than that of horizontal one, while its value is approximately the same for both types of polarization at higher frequencies. Equation (3.112) can be simplified using the first term of Taylor series expansion to the following equation at the particular conditions that $A_{e\gamma}$ is quite less than A_m.

$$\gamma d/A_m \ll 1 \quad \Rightarrow \quad A_{e\gamma} \approx +\gamma d \tag{3.113}$$

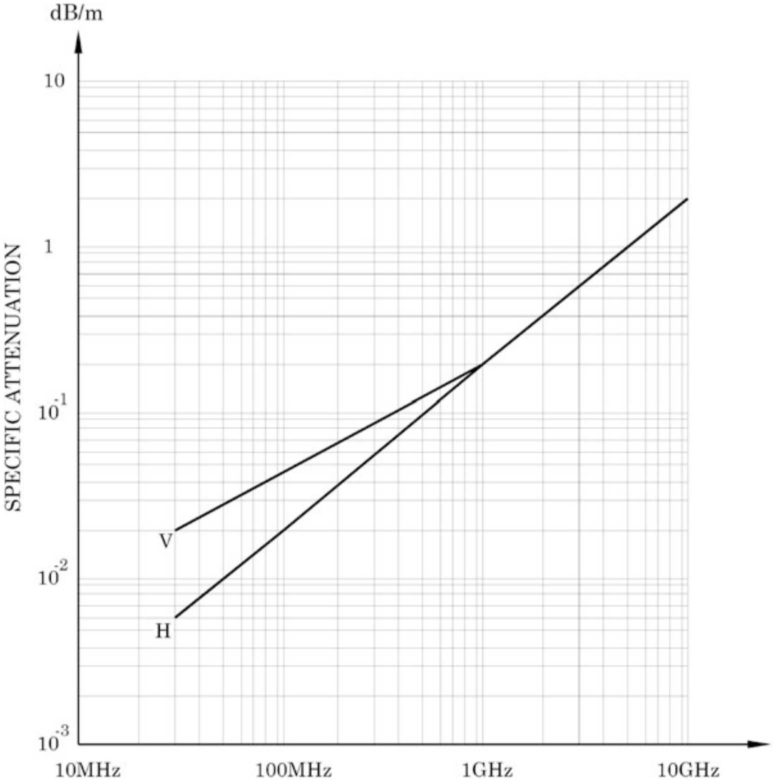

Fig. 3.34 Specific loss index for vegetation and forest areas (Ref.: ITU-R, P-833)

The maximum value of attenuation A_m is a function of frequency as:

$$A_m = A_1 f^{\alpha} \tag{3.114}$$

A_1 and α are experimental coefficients defined at 900 and 2000 MHz frequencies as follows:

- In an area covered with trees in the tropical regions such as Rio de Janeiro in Brazil, a base station transmitter antenna with an average height of 15 m and average receiver antenna height 2.4 m, A_m, is obtained using:

$$A_1 = 0.18\,\text{dB}, \quad \alpha = 0.752 \tag{3.115}$$

- In a moderate vegetation area (such as France), a base station transmitter antenna with an average height of 25 m and average receiver antenna height 1.6 m, A_m, is calculated using:

$$A_1 = 1.15\,\mathrm{dB}, \quad \alpha = 0.43 \tag{3.116}$$

The standard deviation value in recent measurements is 8.7 dB. This value can be used in radio system design using probability theory and statistical methods. Also the variation range of A_m is limited to 2 dB at 900 MHz frequency and 8.5 dB at 2000 MHz frequency.

Considering the above-mentioned results, the following simple and practical equation can be used in radio system design at high VHF frequencies up to 1000 MHz.

$$A_m = \sqrt{f} \tag{3.117}$$

where A_m is in dB and f is in MHz.

Example 3.14. The hand held receiver of a wireless radio-communication system operating in 410–430 MHz frequency band is used inside a forest area; find:

1. Specific attenuation index for vertical polarization.
2. The loss of forest trees in a distance of 80 m.
3. The maximum value for trees excess loss.

Solution. 1. Using Fig. 3.34, it results:

$$\gamma_V = 0.1\,\mathrm{dB/m}$$

2.

$$L_V = 0.1 \times 80 = 8\,\mathrm{dB}$$

3. Using Eq. (3.117), it can be concluded that:

$$A_m = \sqrt{f} \quad \Rightarrow \quad A_m = \sqrt{420} = 20.5\,\mathrm{dB}$$

■

3.9.3 SHF/EHF Frequency Bands

Because of recent developments and growing demand for broad-band wireless access systems, the loss of forests, jungles, parks, and green plant areas for these types of radio links has been taken into account.

These networks have star configurations including a central hub with appropriate tower and antenna and a number of remote stations with small roof-mounted antennas installed at special locations. In most cases, the signals that encounter trees are detected by receivers.

Table 3.5 Tree parameters for calculation of A_s

Parameter	With leaves	Without leaves
a	0.2	0.16
b	1.27	2.59
c	0.63	0.85
k_0	6.57	12.6
R_f	0.0002	2.1
A_0	10	10

The loss occurred in this situation for vertical and horizontal polarizations is the same and includes the following two important factors with different mechanisms:

- Loss of radiowave scattering denoted by A_s while radio signal passes through trees and their leaves
- Loss of radiowave diffraction denoted by A_d while radio signal encounters a mass of trees

The two above factors should be calculated for each particular case, and the dominant one which causes lower loss should be taken into account.

3.9.3.1 Scattering Loss

Scattering loss is calculated according to the following equation:

$$A_s = R_\infty d + K[1 - e^{-\frac{R_0 - R_\infty}{K} d}] \tag{3.118}$$

R_0, is the initial slope of A_s and is equal to:

$$R_0 = a \cdot f \tag{3.119}$$

and R_∞ is the final slope of A_s and is equal to:

$$R_\infty = b/f^c \tag{3.120}$$

Finally, the value of K can be obtained using the following equation:

$$K = K_0 - 10\ \log[A_0(1 - e^{-\frac{A_{\min}}{A_0}})(1 - e^{-f \cdot R_f})] \tag{3.121}$$

The above equations demonstrate dependency of A_s on the frequency in GHz range. The values of parameters a, b, c, K_0, R_f and A_0 are presented in Table 3.5.

$A_{\min}$ indicates the minimum coverage area of wave radiation and can be calculated by multiplying the width of area by the average height of trees and plants covering the transmitter and receiver antennas. The minimum value of

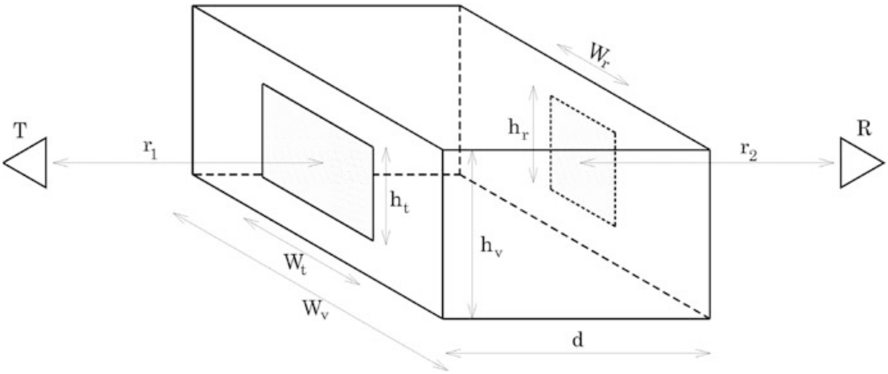

Fig. 3.35 Geometry concept for calculation of $A_{\min}$

the above factors is calculated based on the half-power (−3 dB) beamwidth of azimuth/elevation (A_z/El) patterns of the transmitter and receiver antennas.

According to the above-mentioned facts and Fig. 3.35, if θ_t and ϕ_t are the half-power beamwidth angles regarding the Az/El of the transmitter antenna, respectively, and also if θ_r and ϕ_r are similar beamwidth angles of the receiver antenna, it can be shown that:

$$\begin{aligned} A_{\min} &= \min(h_t, h_r, h_V) \times \min(W_t, W_r, W_V) \\ &= \min\left[2r_1 \tan\left(\frac{\phi_t}{2}\right), 2r_2 \tan\left(\frac{\phi_r}{2}\right), h_V\right] \\ &\quad \times \min\left[2r_1 \tan\left(\frac{\theta_t}{2}\right), 2r_2 \tan\left(\frac{\theta_r}{2}\right), W_V\right] \end{aligned} \tag{3.122}$$

Normally in practice $r_1 \gg r_2$ and also since the half-power beamwidth of receiver antenna is a very small value because of directivity, so the terms including r_1 in the above equation can be neglected.

After calculating A_s and A_d, the following two factors should be calculated. A_d/h corresponding to the diffraction loss caused by top edge of the obstacle and also A_d/w regarding the diffraction loss from side edges based on the provided equations. Then the dominant one out of A_s, A_d/h, and A_d/w should be selected. In Fig. 3.36, the loss caused by the leaves of tree is presented for the minimum radiation area between 0.5 and 2 m^2 and frequencies equal to 5, 10, and 40 GHz. Also the loss value for the similar case but for trees without leaves is shown in Fig. 3.37.

Several researches have been implemented to investigate polarization effect of forest areas, and it is demonstrated that when a radio-wave at 3 GHz frequency band passes through trees in jungles or vegetation areas, especially for long distances, polarization of the wave changes considerably. Also if the path length among trees in forest increases, the received signal level for the original and perpendicular

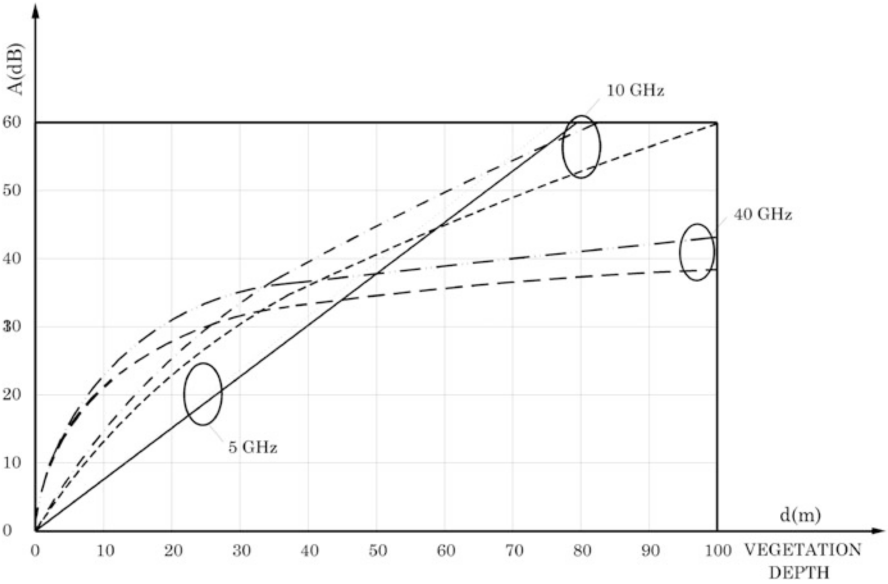

Fig. 3.36 The loss due to vegetation and trees with leaves

polarization decreases, and it falls bellow sensitivity threshold level of receivers which cause interruption in signal transmission.

Example 3.15. The antenna of a radio network in a remote station working at 10 GHz band is located in a place that waves radiated by the main station antenna need to pass through trees with a length of about 40 m. If the minimum area of half-power wave width is equal to 2^2 and diffraction loss for both top and side edge is equal to 35 dB, find:

1. The loss value in the summer for trees with leaves
2. In winter for trees without leaves

Solution. 1. Using the Fig. 3.36 for trees with leaves and $d = 40\,\text{m}$, $A_{\text{min}} = 2\,\text{m}^2$ and $f = 10\,\text{GHz}$, the following value for A_s can be obtained:

$$A_s = 40\,\text{dB}$$

Comparing this value to A_d, it is clear that $A_d/h = 30\,\text{dB}$ is the dominant one.

2. Using Fig. 3.37 for trees without leaves and $d = 40\,\text{m}$, $A_{\text{min}} = 2\,\text{m}^2$ at $f = 10\,\text{GHz}$, it results in:

$$A_s = 30\,\text{dB}$$

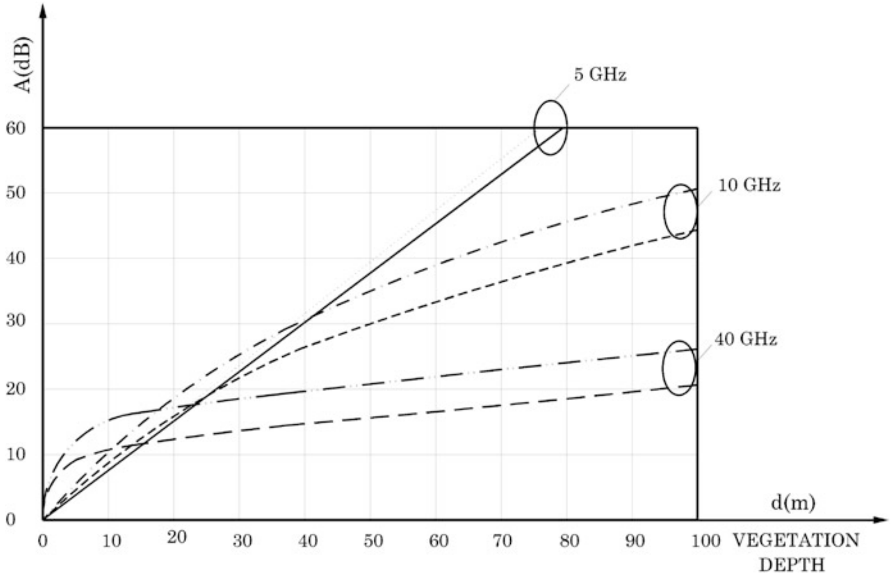

Fig. 3.37 The loss due to vegetation and trees without leaves

Comparing this value to A_d, it can be concluded that $A_s = 30\,\text{dB}$ is the dominant one. ■

3.10 Summary

The following issues related to the troposphere layer were explained, certain phenomena were studied, and theoretical and practical formulas and expressions were introduced:

- Major parameters affecting radiowave propagation were introduced.
- The standard Earth atmosphere was defined and formula to calculate ϵ_r in lower part of troposphere was given.
- Radiowave refraction in the troposphere and refractive index of air were indicated.
- Various types of troposphere refraction parameter such as refractivity number, modified refractive index, and refractive modulus were defined.
- Effective Earth radius and path curvature were explained.
- K-factor was defined, and its variation range and key role in radio link design were identified.
- Earth bulge in radio path, radar, and radio horizons were defined and related formulas were derived.
- Atmospheric duct and its basic types were presented.

- Theory of wave propagation inside atmospheric ducts was explained and related formulas were derived.
- Practical issues and impacts of ducts on radiowave propagation were discussed.
- Practical curves indicating maximum elevation angle and minimum frequency for coupling radiowaves in air ducts were presented.
- Tropospheric attenuation including rain, snow, hail, cloud, fog, and aerosols and useful expressions, curves, and tables were presented.
- Reflection of radiowaves was discussed and related formulas were introduced.
- Multipath reception mechanism was explained and its adverse effects were identified.
- Radio coverage diagrams and antenna height gain curves were presented and discussed.
- Fresnel layers were defined, related formulas were derived, and its role in radio link design was introduced.
- Diffraction mechanism was introduced and its parameter was defined.
- Practical procedures are given to calculate field intensity in diffraction, interference, and midpath regions.
- Attenuation for knife-edge and rounded obstacles was discussed, and empirical formulas and practical methods were introduced for calculation.
- Additional losses in woodlands and vegetation areas for VHF, UHF, SHF, and EHF frequency band were explained, and some practical formulas were introduced.

3.11 Exercises

Questions

1. List the main tropospheric wave propagation phenomena and categorize their effects versus frequency.
2. Refer to P series of ITU-R recommendation list in Appendix B of the book, and based on the tropospheric and ionospheric propagation issues, arrange their list.
3. List the important Earth atmosphere parameters in the ionosphere layer and specify their units.
4. What is the approximate value of electrical permittivity index ϵ_r of the atmosphere and specify the factors which affect it.
5. Specify the characteristics of initial and current standard conditions of the Earth atmosphere.
6. Specify the approximate temperature change rate of different atmosphere layers.
7. Which factors affect the Earth atmosphere refraction index.
8. Define the air refractivity number and air modified refractive index and specify their relationship with index of refraction.

9. Define the wave path curvature radius and, actual and equivalent Earth radii, and state their relationship to each other.
10. Define K-factor and investigate its applications in various radio-communications.
11. What is the variation rate of K-factor for different radio-communication systems?
12. Investigate different cases of radiowave refraction referring to Table 3.3.
13. List the factors affecting Earth bulge and state their relations.
14. Define the radar and the radio horizons and specify whether they are constant or variable for fixed transmitter and receiver antenna heights.
15. What is the main reasons of radio duct formation and list its types.
16. State major aspects of the radio ducts.
17. Define critical elevation angle of wave and list the factors on which it depends and state their roles.
18. Define the duct minimum frequency and specify its range according to Fig. 3.11
19. List the main tropospheric layer losses and specify their effects considering the realistic values for different frequencies.
20. Investigate the effect of frequency on different loss sources for radiowaves propagating in the troposphere layer.
21. Indicate effects of the following items on rain loss:

    (a) Frequency
    (b) Rain intensity
    (c) Effective length
    (d) Rain-drop dimensions
    (e) Rain probability percentage
    (f) Polarization

22. Investigate the graphs in Fig. 3.12 regarding the K_l index variations
23. Fig. 3.12 shows K_l index variations regarding the cloud and fog. Investigate this graph and determine the value of K_l at 10, 20, and 100 GHz frequencies.
24. Determine water vapor and air oxygen attenuation according to the graph in Fig. 3.14 and fix the critical frequencies where related losses increase sharply.
25. What are the main characteristics of reflected waves?
26. What is the Brewster angle? In which type of polarization it occurs?
27. What is the meaning of negative sign of reflection coefficient.
28. Define the multipath phenomenon and specify the communication systems that are affected by this phenomenon including its effect on radio link design.
29. Define the path gain factor (PGF) by its equation and determine its maximum and minimum values.
30. Explain the coverage diagrams and height gain curve.
31. Define the Fresnel zones and specify the kind of radio links which they are mainly applied.
32. Prove that Fresnel radius is maximum in the middle of its path.
33. Determine the following items considering Fig. 3.24:

    (a) Specify the maximum gain for $R = -1$ and the conditions to satisfy it.
    (b) If the reflection coefficient changes to -0.3, how the answers will change?
    (c) Define the interference and obstructed regions

34. Explain the diffraction phenomenon and its applications.
35. Define the distance and height factors in diffraction equation and specify their relationship.
36. When there is an obstacle in the radio path, specify the conditions for applying either diffraction or LOS condition.
37. Define the knife-edge and rounded obstacles and specify their conditions and dependency on frequency.
38. Define the penetration depth and specify its relationship to the type and frequency of waves.
39. Investigate the wave attenuation when it encounters jungles, forest, or trees, and specify its parameters and factors such as frequency, polarization, and path length.
40. Investigate the wave attenuation for SHF/EHF waves and specify its result.

Problems

1. (a) Calculate values of ϵ_r, n, and N in the Earth atmosphere at an altitude of 2 km.

(b) If the refractivity number of air at sea level and at altitude of 1 km are $N_0 = 289$ and $N_1 = 251$, respectively, find R (radius of radio path curvature) at the height of 200 m above the ground level.

2. Arrange a table which its vertical columns represent ϵ_r, n and N parameters of the air, and its horizontal rows present the height of 500, 1000, 1200, 1600, 2000 m with respect to sea level.

(a) Fill in the table with appropriate values.

(b) Plot changes of $N(h)$ vs. height.

3. (a) Suppose that the refractivity number of air at sea level and at altitude of 1 km are $N_0 = 290$ and $N_1 = 250$, respectively, find R at the height of 500 m above ground level.

(b) Find required conditions to form air duct at an altitude of 1000 m.

4. Assuming that radius of radio path curvature is 26,333 km, find:

(a) K-factor

(b) Equivalent Earth radius

5. The K value range is between 0.9 and 1.3 for 40 km path length.

(a) Find minimum and maximum values of equivalent Earth radius.

(b) Find effective value of K for the path at C-band radiowaves.

6. For transmission system with conditions set in Problem 5, calculate the approximate range of Earth bulge variations, for a point with 10 km distance from the transmitter and also for the middle point of the path.

7. The distance between transmitter and receiver is 20 km; find the Earth bulge for points with 5 and 10 km distance from transmitter for the following conditions.

(a) Standard troposphere.
(b) $K = \frac{1}{2}$.
(c) Compare the results for parts a and b.

8. The path length for a radio-communication system at 4 GHz band is 40 km; find the following values for $K = 0.67$ and $K = 0.45$.

(a) Maximum value of Earth bulge.
(b) First Fresnel radius at these points.
(c) Third Fresnel radius at a point with 10 km distance from transmitter.

9. Heights of TX and RX antennas are 36 m and 25 m, respectively.

(a) Calculate the radar and radio horizons for standard conditions.
(b) Calculate the radar horizon for $K = \frac{2}{3}$.

10. A TV transmitter at UHF band radiates through an antenna at the height of 36 m above ground level; if the city and its suburban area are assumed to be flat, find maximum coverage area of receiver antennas in ground level. Assume $K = 1$ for the worst case.

11. Vertical refractivity gradient of the air in coastal area and at altitude equal to 20 m is $-250\,\mathrm{N/km}$ and resulting in the formation of surface air duct.

(a) Find elevation angle for radiowaves that cross air duct without getting trapped inside it.
(b) Determine maximum elevation angle for coupling of radiowaves in air duct using Fig. 3.10.

12. Find the minimum required frequency for waves to be coupled inside the duct for conditions of Problem 11.

13. Assume a radio link with 30 km path length. If 15 GHz frequency band waves are deployed during maximum rainfall intensity of $R = 50\,\mathrm{mm/h}$.

(a) Calculate the rain specific attenuation and then determine the same value using the graph and compare the results (assume the horizontal polarization for waves).
(b) In case of the rain attenuation is acceptable up to 30 dB for the radio link, find maximum rain specific attenuation.
(c) Discuss about utilizing improvement techniques, including frequency/space/cross band diversity, to enhance radiowave reception during raining.

14. Solve the example (3.7) for $f = 15\,\mathrm{GHz}$, $d = 25\,\mathrm{km}$ and rainfall intensity equal to 50 mm/h.

15. In a region, the probability of rainfall with intensity greater than $R = 30\,\text{mm/h}$ is very low. Plot the curve of rain specific attenuation variations for horizontal polarization considering the following cases:

(a) Variations of $L_R = g(d)$ at frequency of $f = 15\,\text{GHz}$ and for distances up to 50 km
(b) Variations of $L_R = g(f)$ for frequency range $2\,\text{GHz} < f < 15\,\text{GHz}$ and at a distance of $d = 40\,\text{km}$.

16. Fog with $6\,\text{g/m}^3$ density is formed in a region at temperature 10 °C. Find the fog specific attenuation at 38 GHz frequency.

17. (a) Find the loss of satellite radio-waves at 30 GHz frequency in the southern region of India where the probability of cloud formation is 10 %.
(b) Find the oxygen specific attenuation value in this region.

18. Calculate the ratio of reflected and main received signal levels assuming $R = -0.3$ and 8 dB additional loss for reflective path due to longer path length and antenna gain reduction.

19. A radar antenna with a height of 5 m tracks an object at 4 km distance. The object is located at the height of 2 m with respect to ground level and the wavelength is 20 cm.

(a) Find the location of wave reflection point and grazing angle.
(b) Assume that $R = -1$, find PGF ($|F|$) and determine the ratio of received signal level to the main signal level.

20. Path length of a radio link is 30 km and operating frequency is 6 GHz, find:

(a) First Fresnel radius at points with 5, 15, and 20 km distance from the transmitter location.
(b) Geometrical position of points that their total distances from T and R are $\lambda/2$ greater than TR.

21. A knife-edged obstacle is located in the path of a wave which is radiated from a TV UHF transmitter antenna with 10 kW power and 20 dB_i gain. Ratio of obstacle height to the first Fresnel radius is 2.5 and the receiver is located at 40 km distance from transmitter. Find:

(a) Received signal level at the detector point.
(b) Is the received signal detectable by receiver with $-70\,\text{dB}_m$ sensitivity?
(c) Margin value of the received signal, and recommend procedure to increase it.

22. For radio link, difference between obstacle and receiver heights is 100 m, and the obstacle is smooth and rounded with 2 km radius. Considering Fig. 3.30 and operating frequency $f = 600\,\text{MHz}$, find:

(a) Received signal level at the receiver.
(b) What is the received signal level if a 15 dB_i antenna and a cable with $L_T = 7\,\text{dB}$ loss is used at 30 m high.

23. For a radio transmission in a flat desert, 7.5 GHz radio with antenna located at altitude of 24 m is used. If it is desired to receive the signal at a point with distance 2.5 times the radar horizon from the transmitter antenna, find:

(a) Receiver antenna height ($K = 4/3$).
(b) Receiver path gain.
(c) Repeat the case for $K = 1/2$.

24. Radiowaves with 300 MHz frequency encounter a wall with 20 cm thickness. If material properties of the wall are equivalent to dry Earth, find the wave loss value. If the frequency of waves changes to 5 GHz, what would be the loss value for this case?

25. Radiowaves with 30 MHz frequency hit the sea surface. If the wave power in the location of collision is $-20\,\mathrm{dB}_m$ and the receiver sensitivity level is $-120\,\mathrm{dB}_m$, determine whether these waves are detectable by a submarine in 20 m depth of the sea surface or not?

26. For 150 MHz frequency band, find:

(a) Loss specific index of a forest region for horizontal and vertical polarizations.
(b) Loss of radiowave crossing trees in the forest for a length of about 100 m.

Chapter 4
Radiowave Propagation in Ionosphere

4.1 Introduction

In Chap. 3, the fundamental phenomena of troposphere were investigated and their effects on radiowave propagation were explained. This chapter is dedicated to study the main phenomena of radiowave propagation in ionosphere. As shown in Fig. 4.1, this layer basically starts from the height of 50 km above the Earth and extends up to the height of 600 km. Although, in some references, it is addressed up to the height of 1000 km, but the main effects of these phenomena appear at heights up to 600 km.

In case of the radiowaves passing through this layer or somehow penetrate into it, they will be affected by the specific phenomena of this layer. Some of the most common communication systems that experience these effects are those working in MF and HF radio transmission bands as well as satellite and space communication systems where one or both end point terminals are located on the ground. The main ionospheric phenomena, similar to other Earth atmosphere layers, are highly dependent on radio frequency by a nonlinear relation.

4.2 Ionization in Ionosphere Layer

4.2.1 Ionization and Plasma State

The most important property of ionosphere is its ionized gases. The amount of ionized gases in this layer is much higher than the inert gases. This layer can change effectively the electrical properties which are dominant factors with great influence on radiowave propagation. The ionosphere contains a specific state of material known as the forth or plasma state.

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DOI 10.1007/978-3-319-32783-9_4

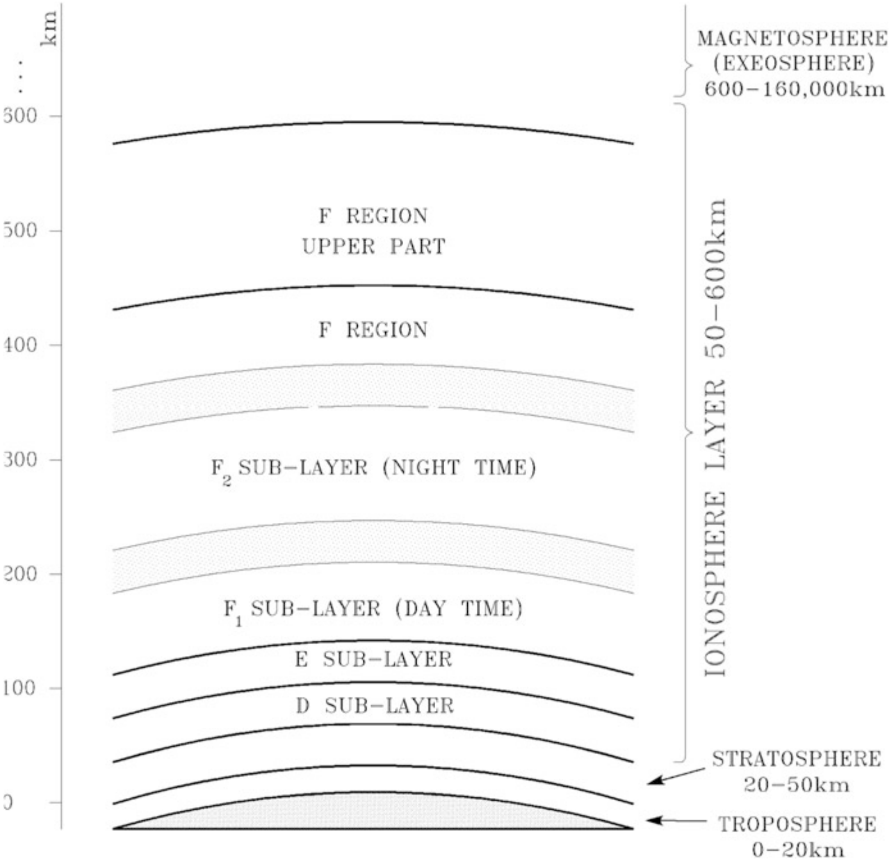


Fig. 4.1 Earth ionosphere structure

Since the ionosphere layer has the majority of plasma properties, therefore, ionospheric researchers and plasma experts are very close to each other. Due to the fact that major part of the visible world is in the plasma state, the study of the plasma is valuable not only for radiowave propagation but also for perception of plasma world.

The plasma environment of Earth and in better expression the ionosphere is not a simple and static layer and it should be studied by periodic monitoring and testing. The Earth is affected by radiation and bombardment of different cosmic rays. Some of these rays have large amplitude and convey considerable amount of energy enabling electrons to be separated from molecules and to form positive and negative ions. The number of free electrons in unit volume is called the plasma density. This parameter is plotted as a function of height in Fig. 4.2.

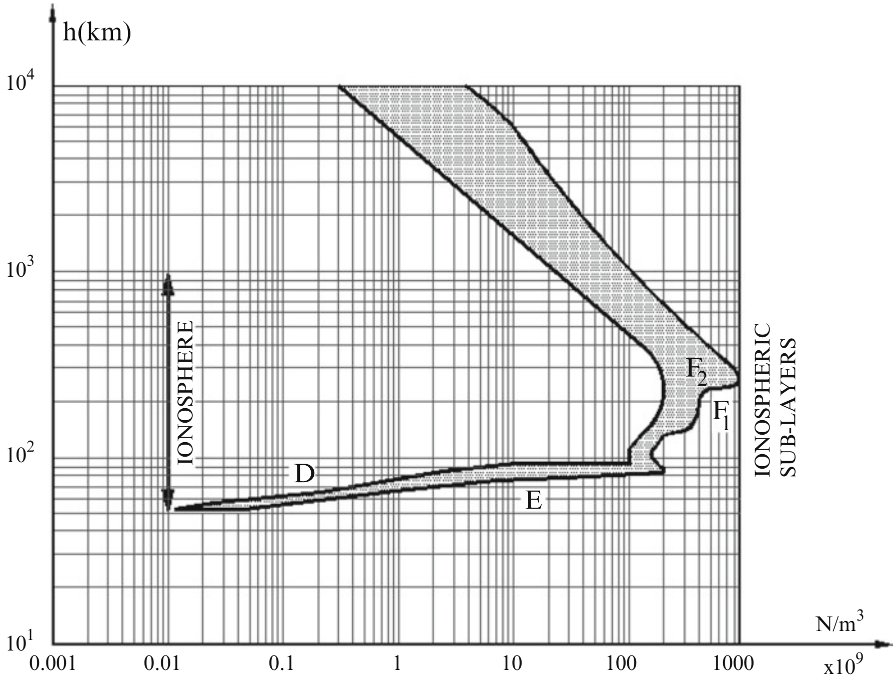


Fig. 4.2 Ionospheric electron density

4.2.2 Ionosphere Layer Classification

Various types of cosmic rays ionize different molecules in the air atmosphere. This stratifies the ionosphere in different heights into different sub-layers. The plasma density has usually a considerable value in the range of 10^9 el/m^3 at heights from 50 to 70 km above the Earth surface which is called D layer. At the altitudes between 70 and 100 km which is called E layer, the plasma density reaches its relative maximum value, and after that, it starts to decrease and again it reaches its absolute maximum value at heights up to 1000 km which is called F layer, and beyond it is a layer called magnetosphere.

During day time, F layer is divided into two sub-layers called F1 and F2 due to sunlight. These two sub-layers merge again at night time to form a single layer.

4.2.3 Ionospheric Phenomena

When the radiowaves pass through or penetrate into the ionosphere, they are affected by different phenomena. Some of the most important ones are listed below:

- Faraday rotation
- Propagation delay and group delay
- Refraction/reflection
- Dispersion
- Absorption
- Scintillation

The first four items depend on the plasma state of ionosphere. The total number of electrons in a cylinder with a cross section of one square meter in solar zenith direction is called TEC and measured in terms of el/m^2. TEC is used as an essential parameter to evaluate the quality of ionosphere. The nominal value for different states of ionosphere layer is in the range of 10^{16}–10^{18} el/m^2. Most of Ionospheric phenomena have statistical properties and depend on different factors such as:

- Geographical latitude and longitude and geomagnetic location
- Earth orbital motion or seasonal effects
- Earth rotation motion or diurnal effects
- Solar activities, especially the number of sunspots
- Magnetic storms
- Geomagnetic field effects

Considering the above factors and their statistical relationship to each other, the ionospheric telecommunications have wide range of changes which shall be taken into account ensuring a reliable and efficient communications.

Example 4.1. 1. Determine the approximate value of plasma density at an altitude of 400 km above the ground level.
2. If the height of D, E, and F layers are 70, 100, and 300 km, respectively, find the value of TEC for each of these layers.
3. Find the effective value of TEC for a satellite transmission using radiowaves with elevation angle equal to 40°.

Solution. 1. Considering the graph in Fig. 4.2, it results in:

$$h = 400\,\text{km} \Rightarrow \quad 1.1 \times 10^{11} \le P_D \le 5 \times 10^{11}\,\text{el/m}^3$$

2. The thickness for each layer is :

$$W_D = 20\,\text{km}, \quad W_E = 40\,\text{km}, \quad W_F = 190\,\text{km}$$

Considering the graph in Fig. 4.2, the average density of each of the above-mentioned layers is approximately:

$$P_{D/D} \approx 1 \times 10^8\,\text{N/m}^3\,,\ P_{D/E} \approx 1 \times 10^{10}\,\text{N/m}^3\,,\ P_{D/F} \approx 3 \times 10^{11}\,\text{N/m}^3$$

Therefore:

$$\mathrm{TEC}/D = 20 \times 10^3 \times 1 \times 10^8 = 2 \times 10^{12}\ \mathrm{el/m^2}$$

$$\mathrm{TEC}/E = 40 \times 10^3 \times 1 \times 10^{10} = 4 \times 10^{14}\ \mathrm{el\ /m^2}$$

$$\mathrm{TEC}/F = 190 \times 10^3 \times 3 \times 10^{11} = 5.7 \times 10^{16}\ \mathrm{el/m^2}$$

3. If the number of electrons is ignored in the space above 300 km, the value of TEC for vertical radiation is calculated as:

$$\mathrm{TEC} = \mathrm{TEC}/D + \mathrm{TEC}/E + \mathrm{TEC}/F \approx 5.75 \times 10^{16}\ \mathrm{el/m^2}$$

In the given satellite communication, since the radiation path is inclined, so the effective value of TEC is equal to:

$$(\mathrm{TEC})_e = (\mathrm{TEC}) \times \sec 45^\circ = 8.1 \times 10^{16}\ \mathrm{el/m^2}$$

■

4.3 Ionospheric Communications in MF/HF Frequency Band

4.3.1 Radiowave Propagation in Ionosphere

Ionosphere has a lot of effects on radiowave propagation. The effects on satellite radiowaves will be studied in the next section. Under some conditions, when the emitted radiowaves in MF and HF bands toward ionosphere encounter this layer, they are reflected back to the Earth.

It is noticeable that the mechanism of radiowave trajectory variations at MF and HF bands in different layers of ionosphere are based on the refraction theory. As demonstrated in Fig. 4.3, the wave radiated toward the ionosphere, starts to deviate from the direct path and subject to some specific conditions return back to the Earth. The deviation occurs because of the changes in the value of ϵ_r and therefore in refractive index of ionosphere with respect to lower layers and provides a very effective media for ionospheric communications.

As shown in Fig. 4.3, return of waves toward the Earth is quite similar to the wave reflection phenomenon which occurs at a virtual height denoted by $h'E$, $h'F1$, and $h'F2$ corresponding to the layer in which the reflection occurs.

Despite the fact that the E and F layers exist all the time, their relative heights are changed during day time and night time. Since the communication path length, or distance between the transmitter and the receiver at a particular frequency and a specific antenna radiation pattern, depends on the reflection point location, so the

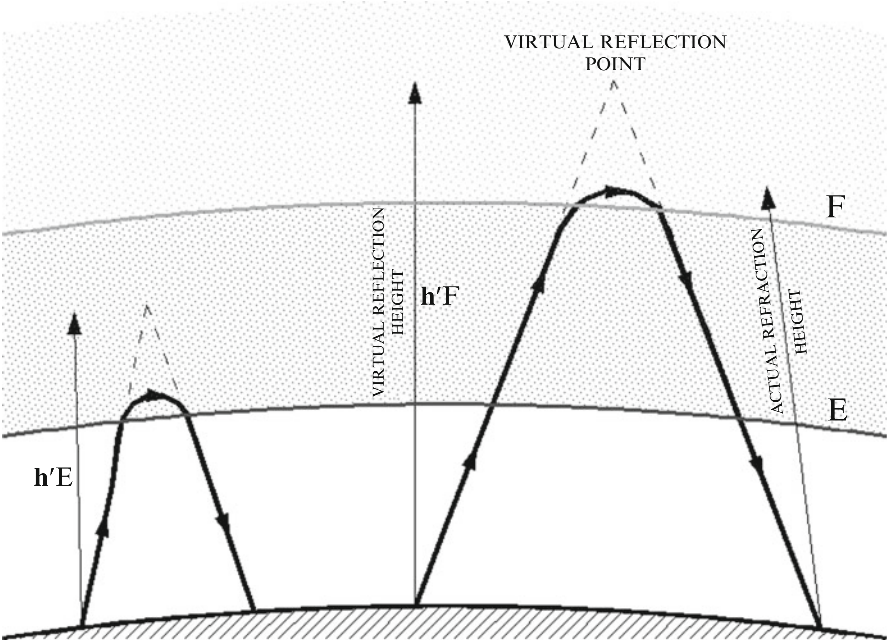


Fig. 4.3 Radiowave refraction in ionosphere

effective range of communication is time varying and generally different at day and night periods.

In the D layer the electron collision is too much and even the waves with lower frequencies than 2 MHz can be reflected, but the attenuation value at these frequencies is too high because of atmospheric absorption. Considering this fact and because of the D layer existence at lower heights during day time, the range of ionospheric radio transmission at a particular frequency is limited and the quality of transmission is lower than the same transmission condition at night time.

4.3.2 Applications

In previous decades and especially prior to employing satellite communication systems, MF and HF radio transmission systems were widely used for the following applications:

- Marine mobile telecommunications
- Intercountry and intracontinental telecommunications
- Long-distance radio broadcasting

However, nowadays and especially in the two recent decades, these traditional communication systems are replaced by various satellite systems and fiber optical networks for most of applications, because of the improvements and developments in the telecommunications technologies and providing the following issues:

- Enhanced features
- Wider coverage
- Higher quality and reliability
- Better facilities to overcome the adverse effects of diurnal and seasonal atmosphere changes and magnetic storms and sunspots

4.3.3 Vertical Propagation in Ionosphere

In ionosphere the plasma environment forms due to the ionization of the existing molecules. Therefore the dielectric constant (electrical permittivity) is calculated according to the following equation:

$$\epsilon_r = 1 - \frac{Ne^2}{\omega^2 m \epsilon_0} \tag{4.1}$$

In the above equation, the parameters and their units are as follows:

- ϵ_0: vacuum electrical permittivity equal to: $\frac{1}{36\pi} \times 10^{-9}$ F/m
- N: electron density in terms of number per cubic meter
- e: electron charge equal to 1.6×10^{-19} C
- m: electron mass equal to 9×10^{-31} kg

In ionosphere a new parameter called plasma resonance frequency denoted by ω_p, or f_p, is defined as follows:

$$\omega_p^2 = \frac{Ne^2}{m\epsilon_0} \tag{4.2}$$

Therefore, Eq. (4.1) changes to:

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \left(\frac{f_p}{f}\right)^2 \tag{4.3}$$

Due to the above fact, the electric field of propagating plane wave in loss-less plasma environment is:

$$\bar{E} = \bar{E}_0 e^{-j\omega\sqrt{\mu\epsilon}.z} = \bar{E}_0 e^{-j\omega\sqrt{\mu_0\epsilon_0}\left[1-\left(\frac{f_p}{f}\right)^2\right]^{1/2}\cdot z} \tag{4.4}$$

In this case, the propagation constant is:

$$k_c = \omega\sqrt{\mu_0\epsilon_r\epsilon_0} = k_0\left[1 - \left(\frac{\omega_p}{\omega}\right)^2\right]^{1/2} = k_0\left[1 - \left(\frac{f_p}{f}\right)^2\right]^{1/2} \tag{4.5}$$

And therefore, the plane wave electric field is simplified to:

$$\bar{E} = \bar{E}_0 e^{-jk_c z} \tag{4.6}$$

Considering different values for f_p and f (or ω_p and ω), there may be the following three possibilities:

1. :$f > f_p$: k_c is a real value and the wave propagates in the desired direction toward the space.
2. :$f < f_p$: k_c is an imaginary value and the radiation in the initial direction is damped sharply (evanescent wave)
3. :$f = f_p$: $k_c = 0$ and f is called critical frequency denoted by f_c.

As shown in Fig. 4.4, the propagating waves with frequencies less than f_c cannot pass this layer and reflected back to the Earth. Using (4.2), critical frequency, f_c, can be approximated by:

$$f_c = 9\sqrt{N} \tag{4.7}$$

Therefore, the critical frequency is equal to the frequency of waves that propagate with the resonance frequency of plasma.

Critical frequencies are very important and should be considered in radio network design. Frequency planning should ensure a reliable communication by providing appropriate transmission conditions. Value of f_c varies in different layers of the ionosphere which are denoted by f_0E , f_0F1, and f_0F2. According to Eq. (4.7) and

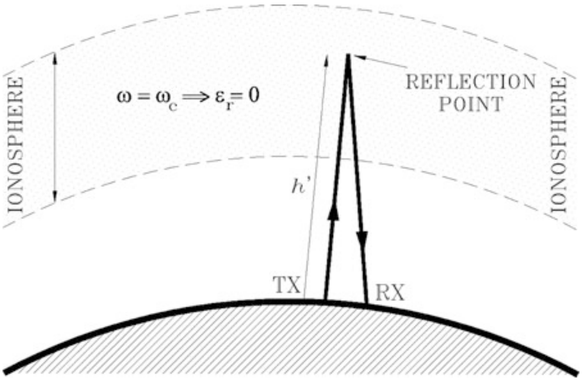


Fig. 4.4 Radiowave vertical propagation in ionosphere

considering the electron density in E, F1, and F2 layers, the critical frequency is in the following range:

$$2.8\ \text{MHz} < f_0E, f_0F1, f_0F2 < 9\ \text{MHz} \tag{4.8}$$

Example 4.2. Electron density in F layer is equal to 5×10^{11} electron per cubic meter.

1. Find the approximate height of this layer.
2. Calculate f_0F frequency.

Solution. 1. Considering the graph in Fig. 4.2 for the given density:

$$h_{\min} = 200\ \text{km}, \quad h_{\max} = 400\ \text{km}$$

2.

$$f_0F = 9\sqrt{N} \approx 6.3\ \text{MHz}$$

■

4.3.4 Inclined Propagation of Ionospheric Waves

Vertical propagation studied in the previous section is an introduction to wave propagation in ionosphere based on a theoretical assumptions. In reality, inclined propagation is usually used to model the radiocommunications in this layer.

As it is shown in Fig. 4.5, the reflection occurs from a virtual point with a more height denoted by h'. Value of this height depends on the wave frequency f and the elevation angle of the incident wave (ψ_i).

To determine the maximum usable frequency denoted by MUF, using layering concept and applying the Snell's law, the following formula is obtained:

$$\sin \psi_i = \sin \psi \times \sqrt{\epsilon_r} \tag{4.9}$$

The wave is reflected back to Earth when $\psi = 90°$; then using Eq. (4.3), it results in:

$$\sin^2 \psi_i = \epsilon_r = 1 - \frac{\omega_p^2}{\omega^2} \tag{4.10}$$

$$1 - \cos^2 \psi_i = 1 - \frac{81\,N}{f^2} \tag{4.11}$$

$$f = \left(\frac{81\,N}{\cos^2 \psi_i}\right)^{1/2} \tag{4.12}$$

$$f = f_C \times \sec \psi_i \tag{4.13}$$

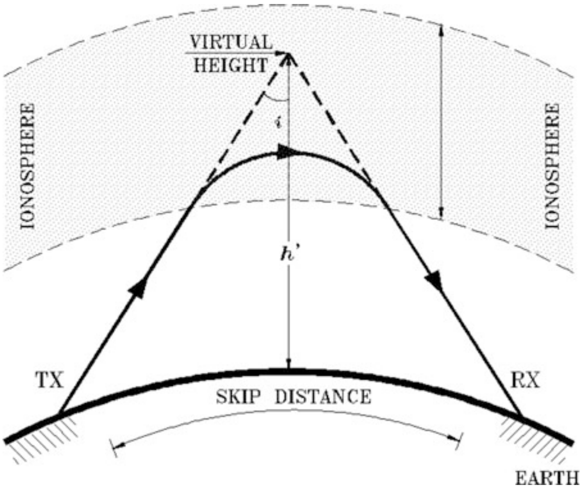


Fig. 4.5 Ionospheric inclined propagation concept

Example 4.3. In the previous example, calculate the maximum usable frequency for 45° elevation angle of radiation.

Solution.

$$f = f_C \times \sec 45^\circ = 6.3 \times \sqrt{2} = 8.883\ \text{MHz}$$

■

4.3.5 Optimum Usage Frequency

To calculate the optimum usage frequency (OUF), the absolute maximum frequency should be determined using Eq. (4.13) and Fig. 4.6. To find the angle, it should be considered that for the case where the waves between transmitter and receiver travel horizontally or tangentially with respect to the Earth surface, we have:

$$\text{MUF} = f_C \times \sec \psi_i \tag{4.14}$$

$$\psi_i = \text{Arc}\ \sin \frac{R_e}{R_e + h'} \tag{4.15}$$

In reality, the radius of Earth and the height of ionosphere F layer are $R_e = 6370\,\text{km}$ and $h' = 200\text{–}400\,\text{km}$, respectively, the result is about 74° for ψ_i, and thus the absolute maximum usable frequency can be calculated as:

$$\text{MUF} = f_C \cdot \sec(74^\circ) = 3.6 f_C \tag{4.16}$$

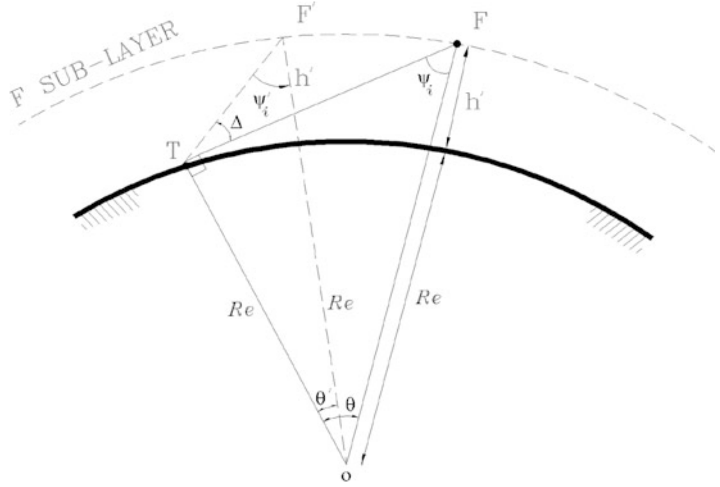


Fig. 4.6 Geometry of inclined propagation path

In this critical condition, the axis of main lobe of radio antenna pattern is absolutely horizontal and the elevation angle of antenna is zero. If for any reason, the elevation angle of antenna is selected to Δ degrees, (dashed line in Fig. 4.6), applying trigonometric formula in triangle $TF'O$ yields:

$$\frac{\sin \psi_i'}{R_e} = \frac{\sin(90 + \Delta)}{R_e + h'} \quad \Rightarrow$$

$$\sin \psi_i' = \frac{R_e}{R_e + h'} . \cos \Delta \tag{4.17}$$

$$\mathrm{MUF} = f_C \cdot \sec \psi_i' \tag{4.18}$$

f_C is usually a function of electron density in ionosphere which varies due to some factors. Thus using MUF for normal operations is unreliable. Therefore, in HF telecommunications, another parameter called optimum usable frequency denoted by OUF is defined. The value of OUF is usually between 50 and 80 % of the related MUF.

Example 4.4. 1. Calculate the maximum usable frequency for TEC $= 10^{17}$ el/m^2. Assume that the thickness of F layer is 200 km.

2. Determine the optimum usable frequency.
3. If the waves at the frequency of 11 and 23 MHz radiate with elevation angle of 30°, determine whether they can provide a reliable communication or not.

Solution. 1.

$$\text{TEC} = H \times P_D \quad \Rightarrow \quad 10^{17} = 200 \times 10^3 \times P_D \quad \Rightarrow P_D = 5 \times 10^{11}\ \text{el/m}^3$$

$$f_C = 9\sqrt{N} = 6.3\ \text{MHz}$$

2.

$$\text{OUF} < 3.6 f_C \times 80\,\% \quad \Rightarrow \quad \text{OUF} < 18.145\ \text{MHz}$$

3. For the elevation angle of antenna equal to 30°, the maximum usable frequency is:

$$\Delta = 30 \quad \Rightarrow \quad \psi_1' = 56^\circ$$

$$\text{MUF}(30^\circ) = f_C \cdot \sec 56^\circ \ = \ 11.27\,\text{MHz}$$

Therefore, the waves with 11 MHz frequency are capable of reflecting back to Earth, but their condition is critical, because their frequencies are higher than 80 % of maximum usable frequency. Also, waves with 23 MHz frequency for the given condition are not capable of reflecting back to Earth; they escape from the ionosphere and penetrate into the space. ■

4.3.6 Long-Distance Communications

In the ionospheric communications, the distance between the transmitter and the receiver for one hop may reach hundreds and even thousands of kilometers. The hop distance depends on:

- Operating frequency
- Elevation angle of transmitted wave
- Acting sub-layer in the ionosphere

When the distance between the transmitter and the receiver is greater than the maximum distance $d_{\max}$, it is not possible to establish communication through a single hop and more than one hop is required by utilizing the wave reflection from the Earth as illustrated in Fig. 4.7.

In ionospheric communications, different transmission modes are denoted by xn, where n is the number of hops and x is the used ionosphere layer (e.g., E, F1, and F2).

For instance, transmission mode 3F2 means that 3 hops are used and the wave reflects back from ionospheric sub-layer F2. In Fig. 4.7, examples of different transmission modes that can handle radiocommunications up to 10,000 km are shown.

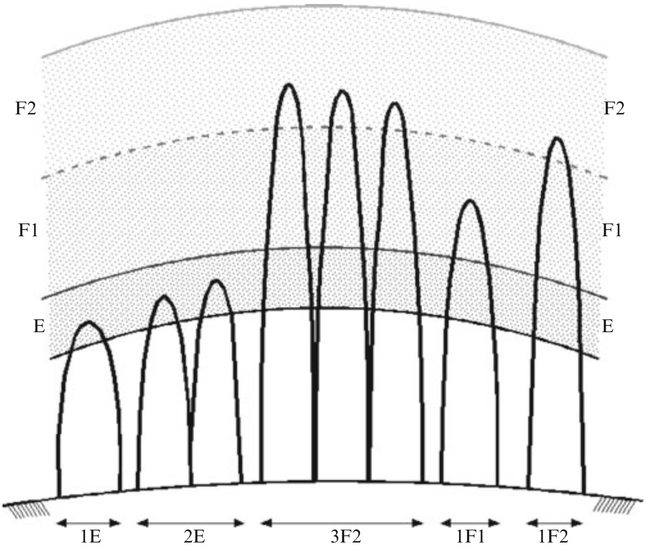


Fig. 4.7 Samples of ionospheric transmission modes

Example 4.5. 1. In example 4.4, when the distance between the transmitter and the receiver is 1000 km, find the approximate value of virtual height of the reflection point.

2. For communication over 1600 km and the same antenna type, what is the appropriate transmission mode?

Solution. 1. According to Fig. 4.6 and with acceptable accuracy for angle $\varDelta = 30°$, it results in:

$$\frac{d}{2} = R_e\theta' \quad \Rightarrow \quad \theta' \approx 0.0786\,\text{rad} \;\approx 4.5°$$

$$\psi_i' = 90 - \varDelta - \theta' \quad \Rightarrow \quad \psi_i' = 55.5°$$

Trigonometric relation in OTF yields:

$$\frac{\sin\psi_i'}{R_e} = \frac{\sin(90 + \varDelta)}{R_e + h'} \quad \Rightarrow \quad h' \approx 324\text{ km}$$

2. If the angle of radiation $\varDelta \approx 30°$ is assumed for this case, it is obvious that 2F transmission mode should be used. By increasing ψ_i, i.e., decreasing $\varDelta$, then the 1F mode also can be used. The other transmission modes such as 1E, 2E, and 3E can be investigated considering the elevation angle of antennas. ■

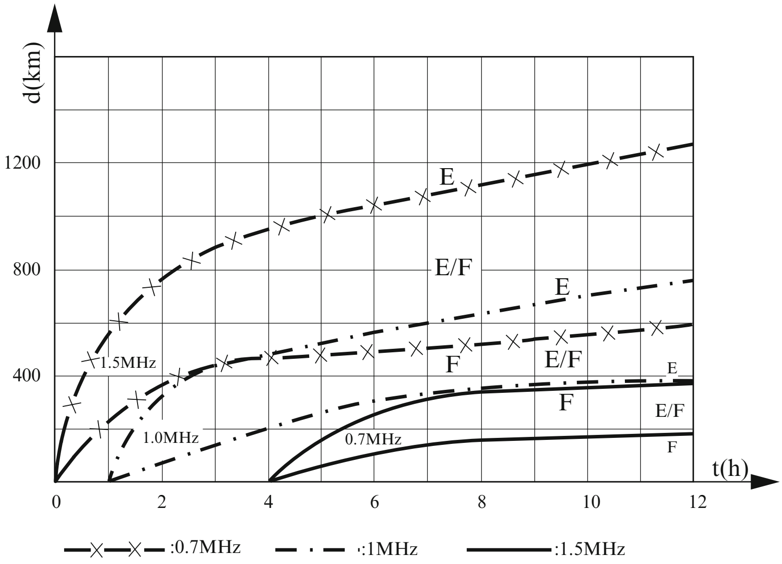


Fig. 4.8 MF band radio path length after sunset (Ref.: ITU-R, P-1321)

4.3.7 *Effects of D Sub-layer and Day/Night Frequencies*

During day time, the loss of ionospheric waves is too high due to the lower part of D sub-layer in such a way that the radiocommunications in MF band becomes too difficult. In practice, to make radiowaves being capable of reflecting back toward the Earth efficiently, higher frequencies are used in MF/HF communications.

Also, during day time, the F layer is divided into two F1 and F2 sub-layers, therefore, in reflection from F1, the radio link becomes shorter than the F layer at night time. At lower frequencies of MF band, it is not possible to establish communication even in hours after sunset. As shown in Fig. 4.8, the time after sunset when the communication is not possible at 700 kHz, 1 MHz, and 1.5 MHz frequencies, they are given according to ITU-R, P.1321 recommendation.

4.3.8 *Time Delay of Different Transmission Modes*

As demonstrated in Fig. 4.9, both ionospheric and ground waves can simultaneously propagate at lower MF frequencies. It is obvious that ground waves because of their shorter path length are detected prior to the ionospheric waves at the receiver.

The time delay between ground and ionospheric waves depend on the transmission mode. In Figs. 4.10 and 4.11, time delay and the relative amplitude of different transmission modes are depicted with respect to ground waves for 700 kHz and 1 MHz frequency waves.

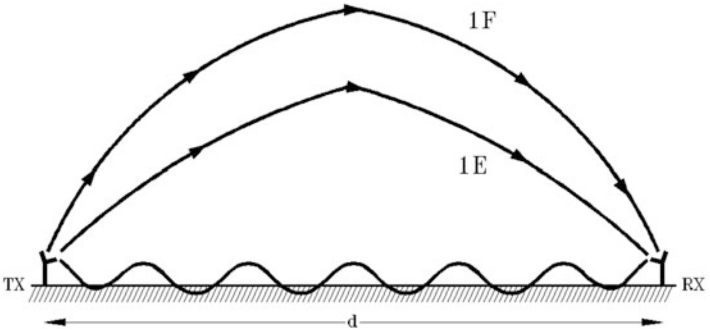


Fig. 4.9 Ionospheric and ground waves in lower MF band

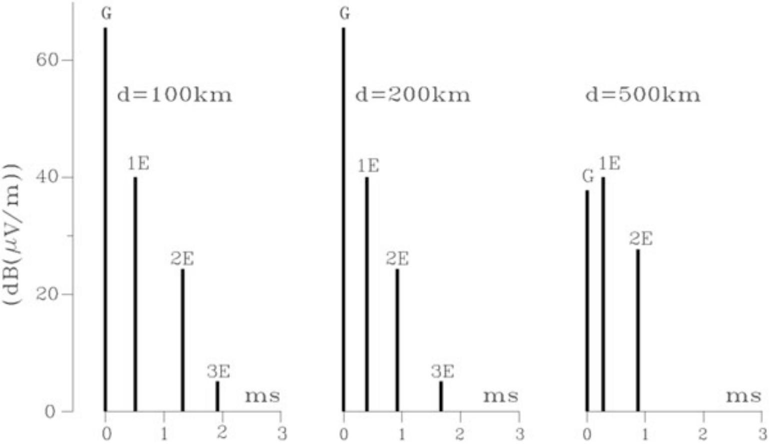


Fig. 4.10 Time delay of ionospheric waves vs. ground waves at 700 kHz (Ref.: ITU-R, P-1321)

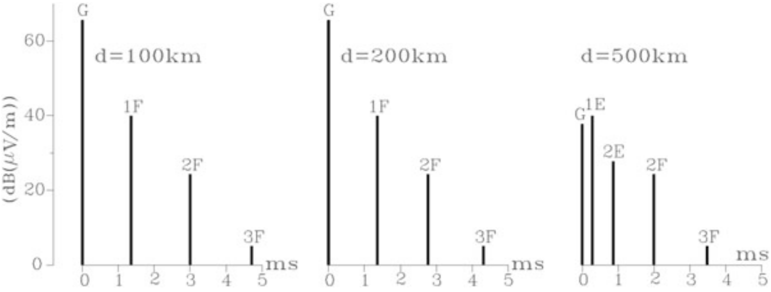


Fig. 4.11 Time delay of ionospheric waves vs. ground waves at 1 MHz (Ref.: ITU-R, P-1321)

The delay of different transmission modes in E and F sub-layers versus radio distance *d* between the transmitter and the receiver is depicted in Fig. 4.12. Also, the relative delays of different transmission modes of a specific layer between the transmitter and the receiver versus the related distance is shown in Fig. 4.13.

Fig. 4.12 Time delay of E and F modes (Ref.: ITU-R, P-1321)

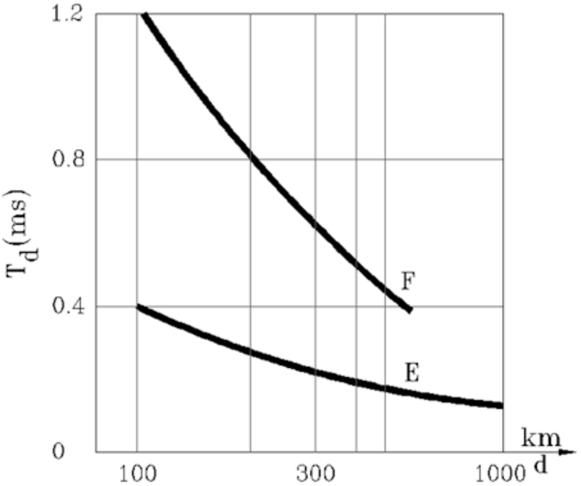
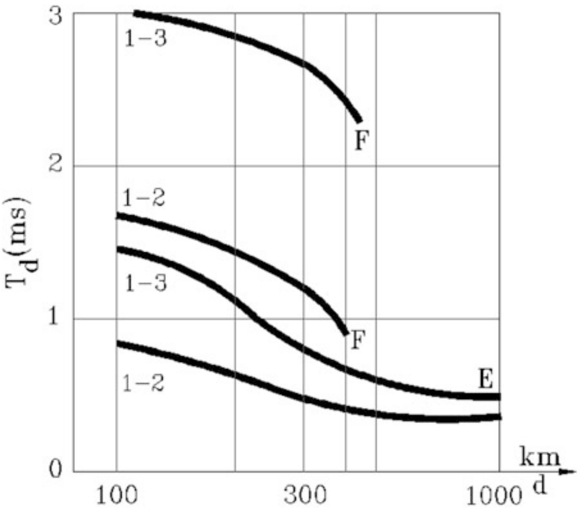


Fig. 4.13 Relative time delay of E and F modes (Ref.: ITU-R, P-1321)



Example 4.6. 1. Find time delay of the first three transmission modes for each of E and F layers for a distance of 200 km and frequency bands equal to 0.7 and 1 MHz, respectively.

2. Determine time delay of E and F transmission modes for a distance of 500 km.
3. Calculate time delay of (1F, 3F) and (1E, 2E) transmission modes for a distance of 300 km.

Solution. 1.

$$d = 200\,\text{km} \Rightarrow (Fig.\,4.10, f = 700\,\text{kHz}) \Rightarrow T_d(1E) = 0.4\,\text{ms}$$

$$T_d(2E) = 0.9\text{ ms}$$

$$T_d(3E) = 1.7\text{ ms}$$

$$d = 200\,\text{km} \quad \Rightarrow \quad (\textit{Fig.}\,4.11, f = 1\ \text{MHz}) \quad \Rightarrow \quad \begin{aligned} T_d(1F) &= 1.3\ \text{ms} \\ T_d(2F) &= 2.8\ \text{ms} \\ T_d(3F) &= 4.3\ \text{ms} \end{aligned}$$

2. The time delay is calculated using Fig. 4.12:

$$T_d(E, F) = 0.3\,\text{ms}$$

3. Using Fig. 4.13:

$$T_d(1F, 3F) = 2.7\ \text{ms}$$
$$T_d(1E, 3E) = 0.5\ \text{ms}$$

■

4.3.9 Solar Effects

The solar effects can be categorized in the following three main aspects:

- Direct effect of sunspots
- Indirect effect of ionosphere layer ionization
- Cosmic noise generation

When electromagnetic waves are trapped in the Sun, they appear as dark spots over the Sun. The main characteristics of these spots are:

- They appear in groups on the Sun surface.
- They are periodic in time and behave as long-term and short-term events.
- Their short-term period is equal to one cycle of rotation of Sun around itself which takes 27.5 days, and the long-term period is about 7–17 years with an average of 11 years.

The number of short-term sunspots in each occurrence is up to 200 and they appear almost once a month. The magnetic field intensity that causes these sunspots can be calculated from ionosphere layer ionization intensity or by measuring the wave reflection at the Earth poles.

Analysis of unwanted signals reveals that there is a noise called cosmic noise generated by sunspots. So, it should be considered in addition to the white noise in radio system design. The number of sunspots is usually determined by ISN and is considered in the range 0–200 in radio system design. The value of ISN can be predicted with acceptable accuracy.

In some cases, another parameter known as solar flux is used instead of ISN. This parameter is radio noise which also called cosmic noise. This parameter is common, because it can be dealt with as the noise power. Solar noise is categorized as colored noise because its power density is considerable at the specific frequency band of $\Delta f = f_2 - f_1 = 2800\,\text{MHz}$.

4.3.10 Geomagnetic Field Effect

The geomagnetic field effect, at frequencies higher than 10 MHz is negligible, but it is considerable at frequencies lower than 5 MHz. The geomagnetic field causes the ionosphere to become a non-isotropic medium, and hence, the effective dielectric coefficient becomes a vector or dyad.

There are two different propagation modes, as follows:

- Ordinary waves
- Extraordinary waves

When a plane radiowave penetrates into the ionosphere, it is divided into the abovementioned radiowave types. When it leaves the layer, the two modes combine again and form a new plane wave with changed polarization plane. This phenomenon is called Faraday rotation which is a varying mechanism, and its effect is a signal loss at the receiver antenna due to the polarization mismatch.

When a free electron with a velocity of $\bar{V}$ is exposed to the magnetic field perpendicular to its direction of motion, it starts to rotate with an angular speed of ω_c called cyclotron frequency. Cyclotron frequency is equal to:

$$\omega_c = \frac{eB_0}{m} \tag{4.19}$$

In the above equation, B_0 is the magnetic field, e is the electron charge, and m is the mass of electron. For instance:

$$B_0 = 5 \times 10^{-5}\ \text{Wb/m}^2 \quad \Rightarrow \quad \omega_c = 8.83 \times 10^6, \quad f_c = 1.4\,\text{MHz}$$

To elaborate Faraday rotation in more details, a plane radiowave propagating along Z axis enters ionosphere layer may be specified by:

$$\begin{aligned} \bar{E} &= 2E_0\, \hat{a}_x e^{-jk_0 z} \\ &= E_0(\hat{a}_x - J\hat{a}_y)e^{-jk_0 z} + E_0(\hat{a}_x + J\hat{a}_y)e^{-jk_0 z} \end{aligned} \tag{4.20}$$

According to Eq. (4.20), the incident wave is divided into two right-handed and left-handed circular polarized waves, and they enter ionosphere layer at a height of

Z_0 with propagation constants K_1 and K_2, respectively. If the reflected waves in the common boundary are ignored, then the outgoing electric field for l meter thickness of atmosphere is:

$$\hat{E} = E_0(\hat{a} - J\hat{a}_y)e^{-jk_1 l} + E_0(\hat{a} + J\hat{a}_y)e^{-jk_2 l} \tag{4.21}$$

which can be rewritten as:

$$\bar{E} = 2E_0 e^{-j(K_1+K_2)\cdot l/2}[\hat{a}_x \cos(K_2 - K_1)l/2 + \hat{a}_y \sin(K_2 - K_1)l/2] \tag{4.22}$$

It means that the outgoing wave is a plane wave with linear polarization and its directional change is equal to angle ϕ according to the following equation:

$$\tan\phi = \frac{E_y}{E_x} = \tan(K_2 - K_1)l/2 \tag{4.23}$$

$$\phi = \tan(K_2 - K_1)l/2 \tag{4.24}$$

When $\omega = \omega_c$ Faraday rotation is considerable and K_1 and K_2 are quite different. But at higher frequencies, K_1 and K_2 are almost equal and Faraday rotation is negligible.

4.4 Ionosphere Effects on Satellite Communications

4.4.1 *Main Effects*

The effects of ionosphere on radio propagation at frequencies up to 12 GHz are significant, especially for MEO and LEO satellites that use frequencies below 3 GHz. Therefore, ionospheric phenomena in satellite radio link design should be considered including the following items:

- Polarization rotation known as Faraday rotation
- Excess time delay called group delay
- Variation in the direction of arrival of the signal
- Doppler effect
- Dispersion and distortion of group velocity
- Scintillation that causes negative effects on wave amplitude, phase, and angle of arrivals

Due to the complicated nature of ionosphere, it is too difficult to describe the effects with analytical formula; so, the best approach is to model them and use supplementary tables and graphs which are based on practical experiments and measurements. Also, because of random behavior of ionosphere disorders, these factors can be described only by stochastic terms.

Regarding to the abovementioned facts, the effects of ionosphere layer should be carefully considered in satellite radio link design at frequencies less than 3 GHz such as mobile satellite services, such as Inmarsat, and meteorology (climate monitoring) satellites.

In fact, the effects of solid and liquid particles that are the main parameters of troposphere layer are negligible in comparison with the following parameters in the satellite communication systems.

- Multipath effect near the Earth surface
- Obstacles on Earth
- Low elevation angle of antenna

4.4.2 Ionosphere Ionization

Solar radiation divides the ionosphere into several ionized sub-layers such as D, E, F, and upper region. The characteristics of these sub-layers are their effects on total electron content (TEC).

In all of the abovementioned regions, the ionizations are nonhomogeneous and time varying, which highly depend on the geographical location and Earth magnetic activities. In addition, the ionization has irregular, active, and varying nature in small scale resulting in scintillation and undesired effects on amplitude, phase, and angle of arrivals of satellite radio signals.

Local irregularities in ionosphere act as converging and diverging lenses and cause focusing and defocusing the radiowaves. Additionally, these irregularities cause the refractive index to be highly dependent on frequency, and therefore, ionosphere becomes a dispersive environment for radiowaves. TEC is presented by N_T and can be calculated using the following equation:

$$N_T = \int_s n_e(s) \cdot ds \tag{4.25}$$

In the above equation, s is path length in meters, and n_e is electron density in el/m^3. Even if the path is perfectly determined, the calculation of exact value of N_T is not so easy because the value of n_e changes are subject to diurnal, seasonal, and the solar effects. In order to model it, the value of TEC is often defined for a solar zenith angle direction with unit square meter area. In this case, the TEC value is in fact equivalent to total number of electrons in a vertical cylinder in ionosphere with unit area and its value varies in the range 10^{16} to 10^{18} electron per square meter (el/m^2) and maximum value usually occurs during day time. It is noticeable that there are different approaches to calculate TEC such as International Reference Ionosphere (IRI) approach and Ne Quick method; both of them have acceptable accuracy.

4.4.3 Faraday Rotation

Polarization plane of a linearly polarized satellite wave rotates gradually when they pass through the ionosphere because of geomagnetic field effect and anisotropy of plasma medium. This mechanism is called Faraday rotation denoted by θ, as a function of frequency, geomagnetic field intensity, and TEC by the following equation:

$$\theta = 2.36 \times 10^2 B_m N_T f^{-2} \tag{4.26}$$

where:

- θ : Faraday rotation angle in terms of radian (rad)
- B_m : Average value of geomagnetic field intensity in terms of weber per square meter (Wb/m^2)
- f : Frequency of wave in Hz
- N_T : The value of TEC in terms of electron per square meter (el/m^2)

The variation of θ versus frequency for different values of TEC is depicted in Fig. 4.14. As defined by Eq. (4.26), the value of θ is inversely proportional to the square of frequency and is directly proportional to the B_m and N_T. Since the changes of θ is even, so it is predictable and can be compensated by antenna setting.

Abrupt and unpredictable changes are also possible, because of geomagnetic storms or ionospheric disturbances that cause abrupt changes in the amplitude of signals, especially in tropical regions.

Cross-polarization discrimination (XPD) of antennas, caused by Faraday rotation in terms of dB, can be calculated according to the following equation:

$$\text{XPD} = -20 \log |\tan \theta| \tag{4.27}$$

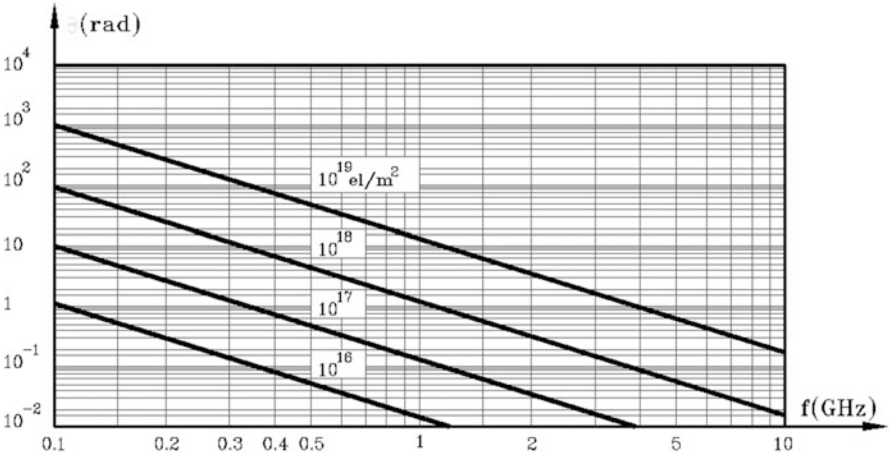


Fig. 4.14 Faraday rotation vs. TEC and frequency (Ref.: ITU-R, P-531)

Example 4.7. For TEC $= 10^{18}$ el/m^2 and the average value of geomagnetic field intensity of 5×10^{-3} Wb/m^2:

1. Calculate Faraday rotation for L-band satellite waves ($f \approx 1.5\,\text{GHz}$)
2. Specify the loss value at the receiver antenna caused by polarization mismatch:

Solution. 1.

$$\theta = 3.36 \times 10^2 \times 5 \times 10^{-3} \times 10^{18} \times (1.5 \times 10^9)^{-2} = 0.7\,\text{rad}$$

2.

$$\text{XPD} = +20\,\log|\tan\theta| \quad \Rightarrow \quad \text{XPD} = -1.48\ \text{dB}$$

■

4.4.4 Group Delay

Presence of charged particles in the ionosphere decreases the velocity of radiowave propagation. The additional time delay with respect to the wave propagation time in the free space is denoted by t and calculated according to the following equation:

$$t = 1.345 \times 10^{-7}\, N_T \cdot f^{-2} \tag{4.28}$$

In the above equation, the parameters and their units are as follows:

- t : Group delay in seconds
- f : Frequency in Hz
- N_T : The value of TEC in the propagation path of inclined satellite waves

Ionospheric time delay versus frequency for different values of TEC is depicted in Fig. 4.15.

4.4.5 Dispersion

For wideband satellite signals, the group delays are varied at different frequencies of the related bandwidth. This mechanism has some adverse effects that cause distortion known as dispersion in received signal. Group delay is directly proportional to TEC and is related to frequency with f^{-3} as demonstrated in Table 4.2. There are some graphs in Fig. 4.16 that show group delay variation versus frequency.

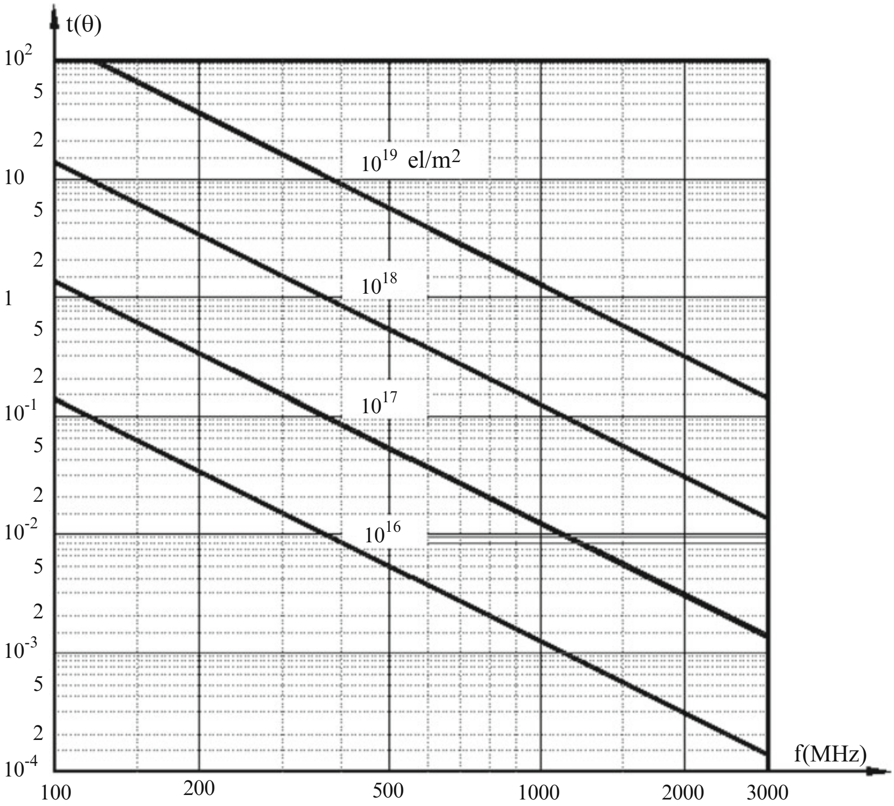


Fig. 4.15 Ionospheric time delay vs. TEC and frequency (Ref.: ITU-R, P-531)

Example 4.8. For satellite waves in L-band ($f \approx 1.5$ GHz), find:

1. Faraday rotation for TEC $= 10^{18}$ el/m^2
2. Ionospheric time delay for TEC $= 10^{17}$ el/m^2
3. Time delay differences for pulses with time duration $\tau = 0.1\,\mu$s

Solution. 1. According to Fig. 4.14:

$$\text{TEC} = 10^{18}, \quad f = 1.5\text{ GHz} \quad \Rightarrow \quad \theta_F = 600\text{ mrad}$$

2. Considering Fig. 4.15:

$$\text{TEC} = 10^{17}, \quad f = 1.5\text{ GHz} \quad \Rightarrow \quad T_l = 5\text{ ns}$$

3. According Fig. 4.16:

$$G/D = 5 \times 10^{-4}\,\mu s \quad \Rightarrow \quad G/D = 0.5\text{ ns}$$

■

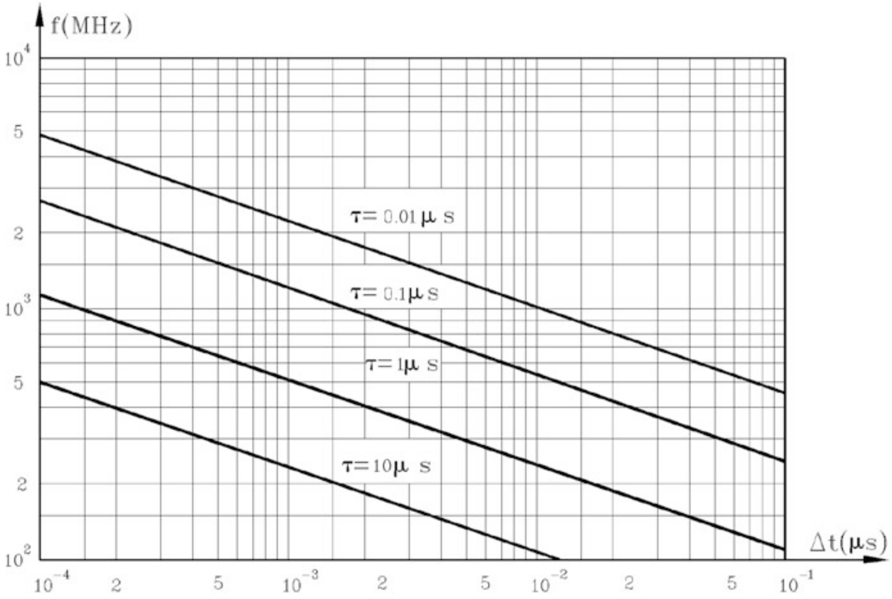


Fig. 4.16 Group delay difference time (Ref.: ITU-R, P-531)

4.4.6 Scintillation

4.4.6.1 Definition

One of the most important negative effects of ionosphere on satellite waves with frequencies less than 3 GHz is scintillation phenomena. Basically, this phenomenon is caused by minor disorders in ionization structure and its density, so there are some changes in different parts of the received waves at the receiver with varying amplitudes, phases, and angles of arrival instead of constant values. This phenomenon has different effects on system performance based on the type of the utilized modulation.

4.4.6.2 Identification Parameter

Identification parameter for scintillation is denoted by S_4 and is defined according to the following equation based on ITU-R recommendations. In the following equation, I is the signal power intensity and $\langle\rangle$ represents the averaging of the indicated parameter.

$$S_4 = \left[\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}\right]^{1/2} \tag{4.29}$$

Table 4.1 Empirical conversion table for scintillation indices (Ref.: ITU-R, P-531)

S_s	P_f (dB)
0.1	1.5
0.2	3.5
0.3	6
0.4	8.5
0.5	11
0.6	14
0.7	17
0.8	20
0.9	24
1.0	27.5

Scintillation coefficient is related to signals peak-to-peak fluctuation and the accurate equation depends on received signal power density. Although, the value of S_4 is mainly less than unity. Because of focusing of disorderly received signals, it sometimes reaches 1.5.

In Table 4.1, S_4 coefficients for different peak-to-peak fluctuations of signal are presented, and these parameters relate to each other according to the following equation with an acceptable accuracy.

$$P_f = 27.5\, S_4^{1.26} \tag{4.30}$$

In the above equation, P_f is in terms of dB.

4.4.6.3 Effective Factors

The factors that have considerable effect on scintillation phenomena can be listed as follows:

- Solar activities
- Geographical location of transmission link
- Diurnal and seasonal effects

4.4.6.4 Estimation of Effects

The following steps can be done to estimate the scintillation effect in a specific condition considering the statistical results and the type of phenomenon in tropical ionospheric paths according to Fig. 4.17:

- In Fig. 4.17 the statistical data are provided for maximum scintillation in different months and different time percentages. The data corresponds to 4 GHz received frequency and location of satellite in eastern hemisphere of Earth with elevation

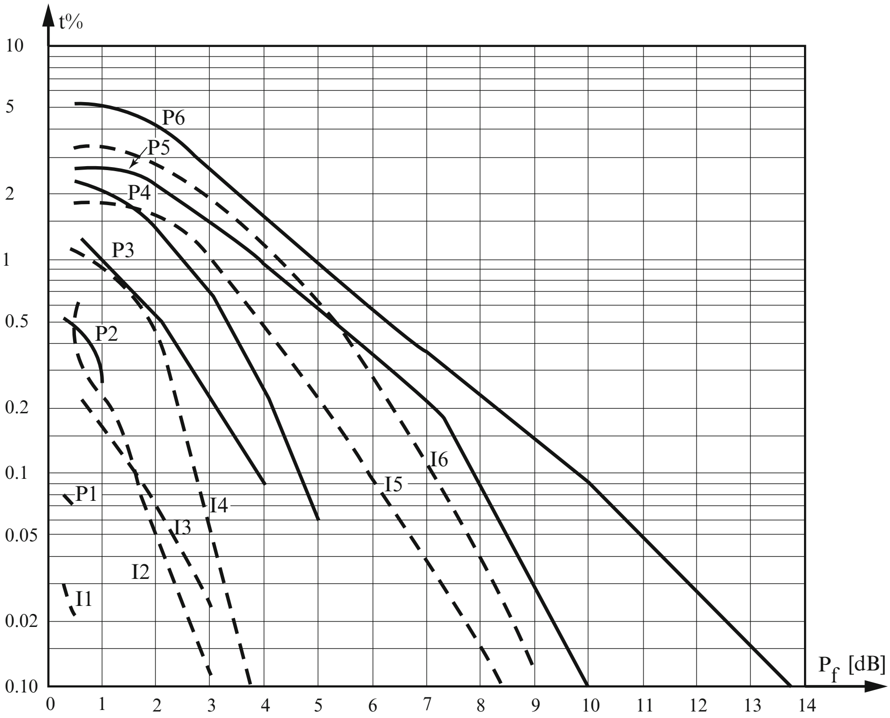


Fig. 4.17 Sample of peak-to-peak fluctuation of I and P_f (Ref.: ITU-R, P-531)

angle about 20° and also for location of satellite in western hemisphere of Earth with elevation angle about 30°.

- The graphs are for 4 GHz; for other frequencies, it should be multiplied by $(f/4)^{-1.5}$ factor where f is the usage frequency in terms of GHz.
- P_f variations versus geographical location should be considered according to the statistical data and the graphs provided in ITU-R, P.531 recommendation.
- As an important factor to calculate link budget, P_f is related to signal loss L_P with equation $L_P = P_f/\sqrt{2}$.
- S_4 coefficient can be calculated according to Eq. (4.29) and using Table 4.1.

4.4.7 Frequency Dependence of Ionospheric Effects

The maximum effects of different factors of ionosphere and their dependency on frequency are presented in Table 4.2 at the frequency of 1 GHz and an elevation angle about 30°. This table is provided in ITU-R, P-531 report and is valid for $TEC = 10^{18}$ el/m^2.

Table 4.2 Estimated maximum ionospheric effects on-way traversal at 1 GHz for elevation angle of about 30° (Ref.: ITU-R, P-531)

Effect	Magnitude	Frequency dependence
Faraday rotation	108°	$1/f^2$
Propagation delay	0.25 μs	$1/f^2$
Refraction	< 0.17 mrad	$1/f^2$
Variation in the direction of arrival	0.2 min of arc	$1/f^2$
Absorption (polar cap absorption)	0.04 dB	$\sim 1/f^2$
Dispersion	0–4 ns/MHz	$1/f^3$
Scintillation	See ITU-R, P-531	See ITU-R, P-531

4.5 Ionosphere Reference Characteristics

4.5.1 Introduction

Considering different factors affecting ionosphere such as Earth orbital motion and rotation, solar effects, magnetic storms, various gases in the Earth atmosphere, and geomagnetic field, it is too difficult to model these phenomena and their relationship with these factors using analytical formulas based on mathematical and physical principles.

For radio link design, service planning, and frequency band selection, long-term ionospheric data and suitable prediction procedures are required. To do so, a number of parameters gathered from different stations all over the world by conducting several long-term measurements and experiments. The collected data are analyzed by international experts and the results of these experimental studies are provided in ITU-R, P.1239 recommendation and its software packages.

When direct information is not available, ionospheric absorption loss can be estimated from available models according to the $(\sec i)/f^2$ relationship for frequencies above 30 MHz, where i is the zenith angle of the propagation path in the ionosphere. For equatorial and mid-latitude regions, radiowaves of frequencies above 70 MHz will assure penetration of the ionosphere without significant absorption.

Measurements at middle latitudes indicate that, for a one-way traverse of the ionosphere at vertical incidence, the absorption at 30 MHz under normal conditions is typically 0.2–0.5 dB. During a solar flare, the absorption will increase but will be less than 5 dB. Enhanced absorption can occur at high latitudes due to polar cap and auroral events; these two phenomena occur at random intervals and last for different periods of time, and their effects are functions of the locations of the terminals and the elevation angle of the path. Therefore, for the most effective system design, these phenomena should be treated statistically bearing in mind that the durations for auroral absorption are of the order of hours and for polar cap absorption are of the order of days. For more information regarding auroral and polar cap absorptions, reference is made to the latest version of ITU-R recommendation P.531.

4.5.2 Mapping Functions

A general numerical mapping function presented by $\Omega(\lambda, \theta, T)$ is defined based on the Fourier time series as follows:

$$\Omega = a_0(\lambda, \theta) + \sum_{j=1}^{H} [a_j \cdot \cos jT \ + \ b_j \sin jT] \tag{4.31}$$

In the above equation, different terms are defined as follows:

Ω: Ionospheric characteristic term to be mapped
λ: Location latitude ($-90° \leq \lambda \leq +90°$)
θ: Location longitude ($0° \leq \theta \leq 360°$) fixed in terms of eastern degree from the Greenwich meridian
T: Universal time (UTC) expressed as an angle ($-180° \leq T \leq 180°$)
H: Maximum number of harmonics for diurnal variation

Fourier series coefficients a_j and b_j are functions of geographical location and are defined by the following series:

$$a_j(\lambda, \theta) = \sum_{k=0}^{K} U_{2j,k} \cdot G_k(\lambda, \theta), \quad j = 0, 1, 2, \ldots, H \tag{4.32}$$

$$b_j(\lambda, \theta) = \sum_{k=0}^{K} U_{(2j-1),k} \cdot G_k(\lambda, \theta), \quad j = 0, 1, 2, \ldots, H \tag{4.33}$$

In a special case, $G_k(\lambda, \theta)$ is defined by integer value k ($k = k_0, k_1, k_2, \ldots, k_m$) where i is the order of corresponding longitude. Considering these facts, the numerical mapping function can be rewritten as:

$$\begin{aligned} \Omega(\lambda, \theta, T) = & \sum_{k=0}^{K} U_{0,k} \cdot G_k(\lambda, \theta) \\ & + \sum_{j=1}^{H} \left[\cos jT \cdot \sum_{k=0}^{K} U_{2j,k} \cdot G_k + \ \sin jT \cdot \sum_{k=0}^{K} U_{(2j-1),k} \cdot G_k \right] \end{aligned} \tag{4.34}$$

$U_{2j,k}$ and $U_{(2j-1),k}$ in Eqs. (4.32)–(4.34) can be represented by general form $U_{s,k}$ where s is either $2j$ or $(2j-1)$. In numerical mapping technique, modified magnetic dip is defined as follows:

$$X = \arctan(I / \sqrt{\cos \lambda}) \tag{4.35}$$

Table 4.3 Geographic coordinate function $G_K(\lambda, \theta)$ (χ is a function of λ and θ, m is the maximum order in longitude) (Ref.: ITU-R, P-1239)

k	Main latitude variation	k	First order longitude	…	k	mth order longitude
0	1	k_0+1	$\cos\lambda\cos\theta$	…	$k_{m-1}+1$	$\cos^m\lambda\cos m\theta$
1	$\sin X$	k_0+2	$\cos\lambda\sin\theta$	…	$k_{m-1}+2$	$\cos^m\lambda\sin m\theta$
2	$\sin^2 X$	k_0+3	$\sin X\cos\lambda\cos\theta$	…	$k_{m-1}+3$	$\sin X\cos^m\lambda\cos m\theta$
.		k_0+4	$\sin X\cos\lambda\cos\theta$	…	$k_{m-1}+4$	$\sin X\cos^m\lambda\sin m\theta$
⋮		⋮			⋮	
k_0	$\sin^{q0} X$	k_1-1	$\sin^{q1} X\cos\lambda\cos\theta$	…	$k_{m-1}-1$	$\sin^{qm} X\cos^m\lambda\cos m\theta$
		k_1	$\sin^{q1} X\cos\lambda\cos\theta$	…	k_m	$\sin^{qm} X\cos^m\lambda\cos m\theta$

where I is the magnetic dip and λ is the geographic latitude. Since X is a function of both geographic longitude and latitude, so the form of $\Omega(\lambda, \theta, T)$ equation will not change. $G_k(\lambda, \theta)$ functions are presented in Table 4.3.

$$q_0 = k_0\ ,\ q_i(i = 1, m) = \frac{k_i - k_{i-1} - 2}{2}$$

The Earth magnetic model for epoch 1960 and 6th order spherical harmonic analysis of modified magnetic depth denoted by X and gyrofrequency f_H are required in the evaluation of the numerical mapping functions. In this respect, since the 1960 reference model is used to define the required coefficients, so it should be used to calculate for other years as well.

Magnetic induction terms of F_X , F_Y, and F_Z in terms of Gauss are along geographic north, east, and vertically downward directions, respectively, and are defined as follows:

$$F_X = \sum_{n=1}^{6}\sum_{m=0}^{n} X_n^m[g_n^m \cos m\theta + h_n^m \sin m\theta] \cdot R^{n+2} \tag{4.36}$$

$$F_Y = \sum_{n=1}^{6}\sum_{m=0}^{n} Y_n^m[g_n^m \sin m\theta - h_n^m \cos m\theta] \cdot R^{n+2} \tag{4.37}$$

$$F_Z = \sum_{n=1}^{6}\sum_{m=0}^{n} Z_n^m[g_n^m \cos m\theta + h_n^m \sin m\theta] \cdot R^{n+2} \tag{4.38}$$

where the X_n^m, Y_n^m, and Z_n^m terms in the above equations are calculated as follows:

$$X_n^m = \frac{d}{d\varphi}[P_{n,m}(\cos\varphi)] \tag{4.39}$$

$$Y_n^m = m \cdot \frac{P_{n,m}(\cos\varphi)}{\sin\varphi} \tag{4.40}$$

$$Z_n^m = -(n+1) \cdot P_{n,m}(\cos\varphi) \tag{4.41}$$

In the above equations, φ is defined as northern colatitude and is equal to $(90-\lambda)$, and $P_{n,m}(\cos\psi)$ is associated Legendre function and is defined as:

$$P_{n,m}(\cos\varphi) = \sin^m\varphi\left[\cos^{n-m}\varphi - \frac{(n-m)(n-m-1)}{2(2n-1)}\cos^{n-m-2}\varphi + \frac{(n-m)(n-m-1)(n-m-2)(n-m-3)}{2\times 4\times(2n-1)(2n-3)}\cos^{n-m-4}\varphi + \cdots\right] \tag{4.42}$$

$g^{m,n}$ and $h^{m,n}$ are numerical coefficients of field model and R is a factor which is related to the location height and is calculated from the following equation. In this equation, h_r is the height of ionosphere layer from ground level in terms of kilometers (for instance, 300 km).

$$R = \frac{6371.2}{6371.2 + h_r} \tag{4.43}$$

According to the above equations and explanations, the total value of magnetic field intensity is equal to:

$$F = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \tag{4.44}$$

Also the magnetic dip and gyrofrequency, f_H, in MHz are determined by the following equations:

$$I = \arctan\frac{F_Z}{\sqrt{F_X^2 + F_Y^2}} \tag{4.45}$$

$$f_H = 2.8F \tag{4.46}$$

4.5.3 Prediction of f_0F2 and $M(3000)F2$

F2 layer mapping function is developed based on the data collected from vertical radiation of waves toward the ionosphere through a lot of ground stations all over the world. Sets of numerical coefficients are identified for diurnal and geographical variations of the monthly median value of f_0F2 and $M(3000)F2$ based on linear relationship with solar activities.

In fact, these coefficients are $U_{s,K}$ values of Eqs. (4.32)–(4.34) for numerical mapping function of $\Omega(\lambda, \theta, T)$ for desired terms in a particular month and level of solar activities. These coefficients are defined for every month of year and for two solar activity values $R_{12} = 0$ and $R_{12} = 100$ where R_{12} is the term of 12-month running average of a number of sunspots and is an index of solar activities.

In most cases, the linear relationship model among R_{12} and both of f_0F2 and $M(3000)F2$ is enough; but in some cases with higher solar activities, this assumption is not valid and a nonlinear relationship exists. Moreover, its value is not constant over time and changes as a function of date and time (diurnal and seasonal). The most important deviation from linear relationship occurs for R_{12} values greater than 150. The prediction error of these cases can be decreased by setting the value of R_{12} to 150.

4.5.4 Prediction of f_0E

The method of predicting monthly median value of f_0E is based on the collected data in 55 ionosphere characteristic measurement stations all over the world between 1944 and 1973. Based on these data, the prediction of f_0E in MHz is given by the following equation:

$$(f_0E)^4 = ABCD \tag{4.47}$$

where, the four factors A, B, C, and D of the equation are defined as follows:

A: The factor of solar activities, given as:

$$A = 1 + 0.0094(\Phi - 66) \tag{4.48}$$

In which, Φ is the monthly average value of 10.7 cm of solar radio flux in terms of $10^{22}\,\mathrm{Wb\,m^{-2}\,Hz^{-1}}$. The approximation of Φ which is equal to its monthly average value Φ_{12} can be used in the mentioned prediction formula with a good accuracy.

B: The seasonal factor given by:

$$B = \cos^m N \tag{4.49}$$

where $N = |\lambda - \delta| < 80°$ and $N = 80°$ are assumed for $|\lambda - \delta| > 80°$. Terms of this equation are defined as follows:

λ: The geographic latitude (it is positive for northern hemisphere)

δ: The angle of solar declination that is considered as a positive value for northern declinations.

m: The exponent factor of Eq. (4.49) as a function of latitude, λ:

$$m = -1.93 + 1.92 \cos \lambda, \quad |\lambda| < 32^\circ \tag{4.50}$$

$$m = 0.11 - 0.49 \cos \lambda, \quad |\lambda| \geq 32^\circ \tag{4.51}$$

C: It is the main factor of latitude which is given by:

$$C = X + Y \cos\lambda \tag{4.52}$$

where

$$|\lambda| < 32^\circ \quad \Rightarrow \quad (X = 23, Y = 116) \tag{4.53}$$

$$|\lambda| \geq 32^\circ \quad \Rightarrow \quad (X = 92, Y = 35) \tag{4.54}$$

D: The factor of daily hour, defined with one of the three following equations based on the solar zenith angle χ:

- Case 1: $\chi \leq 73^\circ$:

$$D = \cos^P \chi \tag{4.55}$$

$$|\lambda| \leq 12^\circ \quad \Rightarrow \quad P = 1.31 \tag{4.56}$$

$$|\lambda| > 12^\circ \quad \Rightarrow \quad P = 1.2 \tag{4.57}$$

- Case 2: $73^\circ < \chi < 90^\circ$:

$$D = \cos^P(\chi - \delta_\chi) \tag{4.58}$$

$$\delta_\chi(^\circ) = 6.27 \times 10^{-13}(\chi - 50)^8 \tag{4.59}$$

P is also given as in the case 1.

- Case 3: $\chi \geq 90^\circ$:

In fact, *D* is related to night hours for $\chi \geq 90^\circ$ and is the greater value out of two values calculated by:

$$D_1 = (0.072)^P \cdot e^{-1.4\,h} \tag{4.60}$$

$$D_1 = (0.072)^P \cdot e^{25.2 - 0.28\chi} \tag{4.61}$$

where h is the number of hours after sunset ($\chi = 90^\circ$). In polar winter, where sun never rises, Eq. (4.61) can always be used. *P* also has the same value given in the case 1.

The minimum value of f_0E is calculated using the following equation:

$$(f_0E)^4_{\min} = 0.004(1 + 0.021\Phi)^2 \tag{4.62}$$

where Φ is also approximated by its 12-month average value Φ_{12}. If the calculated value of f_0E for night is less than the recent value, the minimum value of Eq. (4.62) should be taken. A lot of experiments are conducted to verify the correctness of the above equation. The data collected in more than 80,000 h in 55 ionospheric measurement stations shows that the effective deviation of the median r.m.s. value is limited to 0.11 MHz.

Example 4.9. For $\Phi = 166$, $N = |\lambda - \delta| = 80°$, solar zenith angle $\chi = 60°$ and geographic latitude of 35°, find:

1. The minimum value of f_0E
2. The exact value of f_0E for the mentioned conditions.

Solution. 1.

$$(f_0E)^4_{\min} = 0.004(1 + 0.021 \times 166)^2 \quad \Rightarrow$$
$$(f_0E)_{\min} = 8.05 \times 10^{-2}\,\text{MHz}$$

2. A, B, C, and D factors should be obtained for the given conditions to calculate the value of f_0E using Eq. (4.47)

$$A = 1 + 0.0094(166 - 66) = 1.94$$
$$\lambda > 32° \;\Rightarrow\; m = 0.11 - 0.49\cos\,35 = -0.2914$$
$$(m = -0.2914, N = 80°) \quad \Rightarrow \quad B = \cos^m N = 1.678$$
$$\lambda > 32° \quad \Rightarrow \quad X = 92 \;,\; Y = 35$$
$$C = X + Y\cos\lambda \quad \Rightarrow \quad C = 92 + 35\cos 35° = 120.7$$
$$|\lambda| > 12° \quad \Rightarrow \quad P = 1.2$$
$$D = \cos^P \chi = \cos^{1.2} 60° = 0.417$$
$$(f_0E)^4 = A \cdot B \cdot C \cdot D \quad \Rightarrow \quad f_0E = 3.58\,\text{MHz}$$

■

4.5.5 Prediction of f_0F1

Expressions regarding to the monthly median value of f_0F1 is based on the collected data in 39 ionospheric measurement stations located in northern and southern hemispheres during the years from 1954 to 1966. These expressions are defined for f_0F1 in MHz as follows:

$$f_0F1 = f_s \cos^n \chi \tag{4.63}$$

$$f_s = f_{s0} + 0.01(f_{s100} - f_{s0})R_{12} \tag{4.64}$$

$$f_{s0} = 4.35 + 0.0058\,\lambda - 0.00012\,\lambda^2 \tag{4.65}$$

$$f_{s100} = 5.35 + 0.011\,\lambda - 0.00023\,\lambda^2 \tag{4.66}$$

$$n = 0.093 + 0.00461\,\lambda - 0.000054\,\lambda^2 + 0.0031\,R_{12} \tag{4.67}$$

where λ, the geomagnetic latitude in terms of degree, is assumed as a positive value for both northern and southern hemispheres and is defined by the following equation:

$$\lambda = |\arcsin[\sin g_0 \cdot \sin g + \cos g_0 \cdot \cos g \cdot \cos(\theta_0 - \theta)]| \tag{4.68}$$

In this equation, the parameters are defined as:

g: Geographic latitude of desired location
g_0: Geographic latitude of north geomagnetic pole of the Earth (equal to 78.3°N)
θ: Geographic longitude of desired location
θ_0: Geographic longitude of north geomagnetic pole of the Earth (equal to 69°W)

Example 4.10. Calculate the critical frequency of F1 layer for zenith angle of $\chi = 60°$ and geomagnetic latitude of 50° and solar activity number $R_{12} = 100$.

Solution.

$$\begin{aligned}
f_{s0} &= 4.35 + 0.0058 \times 50 - 0.00012 \times 50^2 = 4.34\\
f_{s100} &= 5.35 + 0.011 \times 50 - 0.00023 \times 50^2 = 5.33\\
f_s &= f_{s0} + 0.01(f_{s100} - f_{s0}) \times R_{12} = 5.33\\
n &= 0.093 + 0.00461 \times 50 - 0.000054\ \times 50^2 + 0.0031 \times 100 = 0.192\\
f_0F1 &= f_s \cos^n \chi \approx 4.9\,\text{MHz}
\end{aligned}$$

■

The maximum value of solar zenith angle in which F1 layer exists is calculated from the following equation in terms of degree:

$$\chi_m = \chi_0 + 0.01(\chi_{100} - \chi_0) \cdot R_{12} \tag{4.69}$$

In this equation, the values of χ_0 and χ_{100} are:

$$\chi_0 = 50.0 + 0.348\,\lambda \tag{4.70}$$

$$\chi_{100} = 38.7 + 0.509\,\lambda \tag{4.71}$$

Figure 4.18 depicts the variation of χ_m versus Earth geomagnetic latitude and for some values of R_{12}.

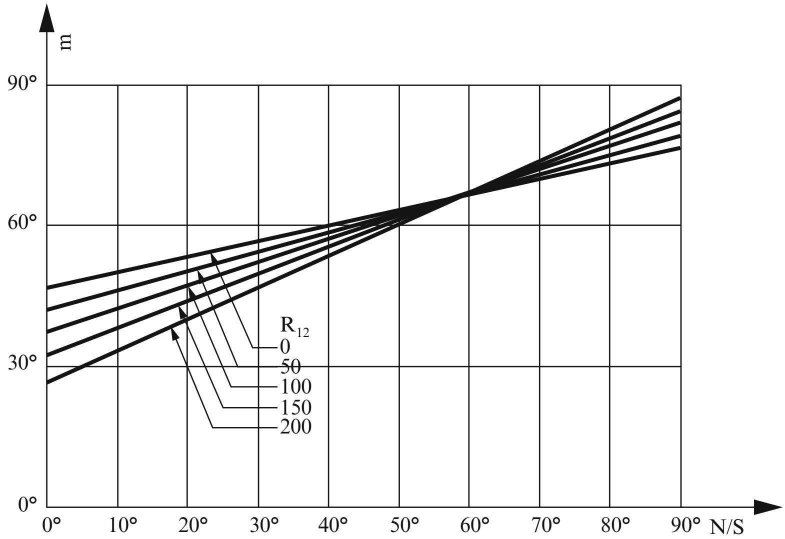


Fig. 4.18 Variation of χ_m with λ and R_{12} (Ref.: ITU-R, P-1239)

The graphs of Earth geomagnetic latitude versus geographical longitude and latitude is also depicted in Fig. 4.19.

4.5.6 Software Programs

Two software programs called WOMAP and HRMNTH are provided by ITU radio division. WOMAP software presents the ionosphere characteristic values for different geographical locations based on universal time, reference month, and solar epoch. The supplementary program of HRMNTH also presents the ionosphere characteristic values in graphs for different locations and years as a function of universal time zone and reference month and the associated solar epoch. In addition, ITU provides useful data for median value as higher and lower (for the years with higher and lower solar activities) as follows:

- Numerical coefficients represent diurnal, geographical, and monthly variations of f_0E
- Numerical coefficients represent diurnal variations of f_0E
- Numerical maps of virtual reflection height-time for vertical radiation from F layer at night time denoted by $h'F$
- Numerical maps of virtual reflection height-time for vertical radiation from F2 layer at day time denoted by F2, $h'F$
- Probability of division of F layer into sub-layers using the mapping methods

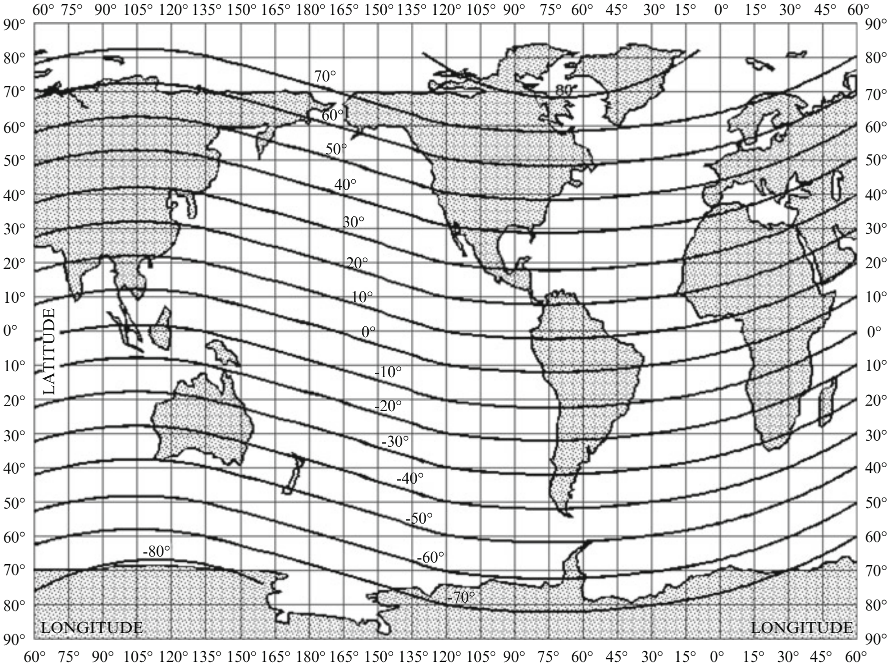


Fig. 4.19 Geomagnetic latitudes vs. geographic coordinates (Ref.: ITU-R, P-1239)

4.6 Ionosphere Main Parameters

4.6.1 Main Indices

The main parameters of ionosphere layer are required to apply in the equations of previous section in order to calculate the critical frequencies related to E and F layers. To do so, the following two Sun-specific parameters should be determined:

- The 12-month average value of number of sunspots denoted by R_{12}
- The 12-month average value of solar radio noise in 2800 MHz band denoted by Φ_{12}

The long-term ionosphere indices are based on their explicit relationship with some of the measurable solar activity parameters. Generally, the variation of solar activities contains the following main terms:

- Relationship with long-term period in the range of 7–17 years with average value of 11 years that specifies one cycle of solar activity.
- Quasi-periodic relationship with time duration slightly less than a year
- Erratic fluctuation with less than a month period equal to one cycle of rotation of Sun around itself equal to 27.5 days.

4.6.2 Sunspot Numbers

In order to study the main component of the solar cycle, it requires the 12-month average value denoted by R_{12}. This index is defined according to ITU-R, P.371 recommendation, as follows:

$$R_{12} = \frac{1}{12}\left[\sum_{n-5} R_K + \frac{1}{2}\left(R_{n+6} - R_{n-6}\right)\right] \tag{4.72}$$

where:

R_{12}: Smoothed index for the month represented by $K = n$
R_K: Daily average value of sunspot numbers for Kth month
$R_{n\pm6}$: The average value of sunspot numbers for a month ($n \pm 6$)

Two main disadvantages of the above expression to calculate R_{12} are:

- The last available value of R_{12} is for at least 6 months before the current month.
- R_{12} value is not applicable to predict short-term variations of solar activities.

Despite the above facts, the smoothed value of R_{12} is the most useful parameter for long-term study of F2 layer.

In some references, the number of sunspots is represented by International Sunspot Number (ISN) which is usually in the range between 0 and 200. In Fig. 4.20, a sample of a number of sunspots is depicted for one solar activity cycle.

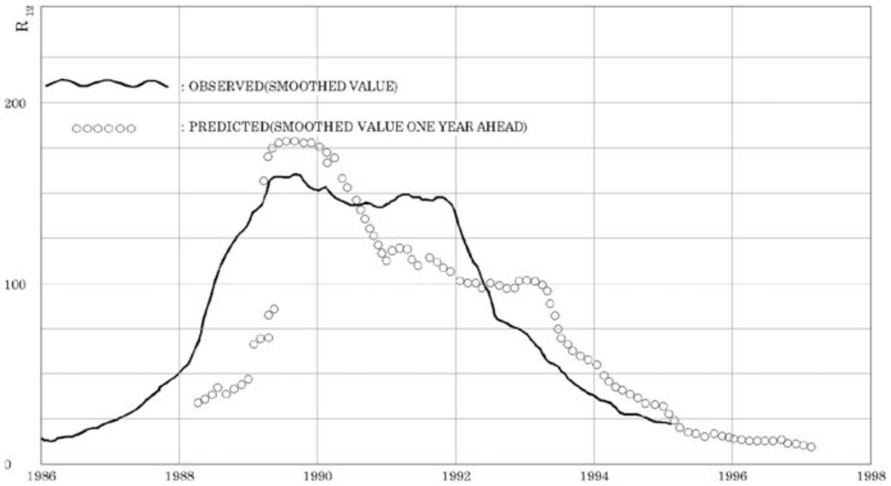


Fig. 4.20 R_{12} variations for a solar activity cycle (Ref.: ITU-R, P-371)

4.6.3 Index Φ

The radio noise flux of solar activities usually corresponds to the wavelength of about 10 cm. The average value of this term is chosen about $10^{-22}\,\mathrm{Wb\,m^{-2}/Hz}$ based on the daily values of Φ in Canada. This typical value is very close to the corresponding value of E layer critical frequency.

The 12-month average values of R_{12} and Φ_{12} are related to each other according to the following equation:

$$\Phi_{12} = 63.7 + 0.728\, R_{12} + 8.9 \times 10^{-4}\, R_{12}^2 \tag{4.73}$$

The relationship between these factors is demonstrated in Fig. 4.21.

In addition to the white noise, there is another type of noise called cosmic noise. This is generated by sunspots and should be considered in radio link design. In some methods, the solar radio noise flux value is used instead of ISN to model the solar effects, because it can be dealt with as a noise power in electromagnetic calculations which is more common. Solar noise is a colored noise, because it appears in a particular range of frequency band, which is equal to $\Delta f = f - f_0 = 2800\,\mathrm{MHz}$.

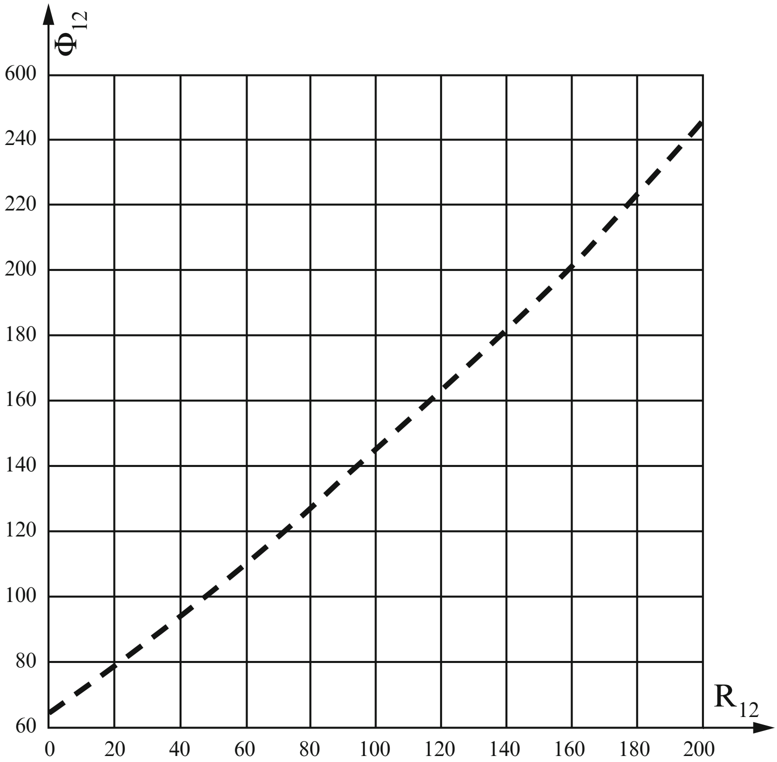


Fig. 4.21 Relation between R_{12} and Φ_{12} (Ref.: ITU-R, P-371)

Example 4.11. 1. Determine the value of R_{12} in 1990 year.
2. Calculate the value of Φ_{12} in this year.
3. Calculate the value of f_0F1 in this year at a location with geomagnetic latitude $\lambda = 30°$ and solar zenith angle $\chi = 45°$.

Solution. 1. Using Fig. 4.20 for 1990, we have:

$$R_{12} = 150$$

2.

$$\Phi_{12} = 63.7 + 0.728 \times 150 + 0.00089 \times 150^2 = 193$$

3.

$$f_{s0} = 4.416, \quad f_{s100} = 5.473, \quad n = 0.23$$
$$f_s = 6 \quad \Rightarrow \quad f_0F1 = 5.54\,\mathrm{MHz}$$

■

4.7 Summary

Ionosphere of the Earth and its adverse effects on radiocommunications as summarized below were studied, and some useful graphs and expressions were presented.

- Earth ionosphere was introduced and its different sub-layers were explained.
- Plasma state was defined and ionospheric resonance plasma frequency was derived.
- Major ionospheric phenomena related to radiowaves including Faraday rotation, propagation delay, refraction, reflection, dispersion, absorption, and scintillation were discussed.
- Total electron content (TEC) of ionosphere was introduced and its normal extremes were stated.
- Key role of ionosphere layer in MF/HF sky waves and their application were mentioned.
- Maximum and optimum usage frequencies (MUF and OUF) were defined and related formulas were expressed.
- Critical frequency for vertical and inclined ray path in D, E, and F layers was defined and formulas were derived.
- Suitable day/night time frequency for long-distance radiocommunications in MF/HF bands was explained.
- Propagation modes in E and F sub-layers were introduced.

- Practical solar effects on ionospheric propagation were recognized and their characteristics were identified.
- Effects of geomagnetic fields on both ionospheric ordinary and extraordinary radiowaves resulting in Faraday rotation were discussed.
- Major ionospheric effects on space radiowaves specially satellite communications including polarization rotation, group delay, dispersion, scintillation, and Doppler effect were discussed, and useful expressions and graphs were given.
- Ionosphere mapping functions were expressed and their mathematical formulas were presented.
- Some software programs were introduced relating to ionosphere characteristics for f_0E, $h'F$, and f_0F prediction.
- A sunspot number and solar noise flux value affecting ionosphere characteristics were explained.
- Useful figures, graphs, and tables based on the relevant ITU-R recommendations were given as applied tools for sky wave link design.
- Frequency dependence of ionospheric phenomena and mechanisms were outlined and listed in a table.

Further system-specific details such as satellite communications, MF/HF sky wave, and other details are provided in the related chapters.

4.8 Exercises

Question

1. Specify different regions of the ionosphere and determine their approximate heights from the Earth surface.
2. Define plasma state and explain its relationship with ionosphere layer.
3. List the main ionospheric phenomena affecting the radiowave propagation.
4. Explain the ionosphere structure considering Fig. 4.2.
5. Explain the virtual reflection height in the ionospheric MF/HF communications and specify the frequencies at which it is not valid.
6. Specify whether the ionospheric MF/HF communications are based on the wave refraction or wave reflection. Why?
7. Specify application of the ionospheric communication systems and also list some of the new applications for this type of communication.
8. Define plasma frequency and explain its exact and rough equations.
9. Define critical frequency denoted by f_c and maximum usable frequency denoted by MUF in vertical radiation and inclined radiation and specify their equations.
10. Define the minimum frequency values of f_0E , f_0F1, and f_0F2 and specify their relative values.
11. Explain different modes of ionospheric radiowave propagation in MF/HF band and specify their applications.

12. Explain D layer and its effects. For what type of radiocommunications is it applicable?
13. List the main effects of ionosphere layer in satellite radio networks especially mobile satellite communications.
14. Specify the main factors of Faraday rotation and explain how they are related to each other.
15. Explain group delay in satellite communications and specify its affecting factors.
16. What is the variation range of Faraday rotation at 2 GHz?
17. Describe dispersion phenomenon in satellite communications and specify the main factors affecting it.
18. Explain scintillation phenomenon in the ionosphere and its affecting factors and characteristic parameters.
19. Define mapping function and related method to determine main parameters of the ionosphere and specify the major factors.
20. Define f_0E and f_0F1 and express the main factors that change their values.
21. Define solar zenith angle and geomagnetic latitude and determine their ranges.
22. Define the main parameters of the ionosphere, determine their exact values, and list their effective items.
23. Write the equation which relates R_{12} and Φ_{12} and compare it with the graph in Fig. 4.21.
24. Specify the units of f_0E , f_H , R_{12} , Φ_{12}, and $h'F2$.

Problems

1. a: Specify the height from the ground level in which the electron density is maximum.

b: What is the variation range of this parameter at the height of 300 km above ground surface?

c: If D, E, and F sub-layers are assumed to be 20, 40, and 180 km, respectively, calculate the value of TEC in a cylinder perpendicular to the ionosphere layer.

2. Calculate the resonance frequency of plasma if $N_T = 10^{16}$ el/m^2 and specify whether the radiowaves with frequency equal to 23 MHz are capable of reflecting back to the Earth from it or not.

3. a: Solve the Example 4.2 for electron density $N = 3 \times 10^{11}$.

b: Find the maximum value of usable frequency MUF, if radiowaves are radiated with elevation angle of 30° into ionosphere.

4. If the ionospheric radiowave reflects back at the height of 300 km:

a: Find the critical frequency for vertical radiation.

b: What is the maximum value of frequency for inclined radiation with elevation angle of 60°?

5. Calculate the maximum usable frequency for the following conditions:

- $\varphi_i = 45°$, $N_1 = 2 \times 10^{10}$ el/m^3
- $\varphi_i = 60°$, $N_2 = 10^{12}$ el/m^3

Find the optimum usable frequency in both cases.

6. If the electron density in the ionosphere is equal to 5×10^{11} el/m^3

a: Calculate the critical frequency.
b: Find the approximate elevation angle for radiowaves with frequency of 15 MHz to be capable of reflecting back to the Earth.
c: Find the maximum radiowave frequency and its radiation conditions for long-distance terrestrial communications.

7. Repeat Example 4.4 for $N_T = 5 \times 10^{17}$ el/m^2 and thickness of F layer equal to 300 km.

8. The ionosphere electron density is assumed to be:

$$h = 110\,\text{km}, \quad N = 1.5 \times 10^{11}\ \text{el/m}^3$$
$$h = 200\,\text{km}, \quad N = 4 \times 10^{11}\ \text{el/m}^3$$
$$h = 400\,\text{km}, \quad N = 6 \times 10^{11}\ \text{el/m}^3$$

What is the appropriate transmission modes if the distance between the transmitter and the receiver would be 1000, 4000, and 8000 km?

9. Considering Fig. 4.8, determine the appropriate radio frequency and transmission mode for communication between two points with distance greater than 400 km beyond 2 h after sunset.

10. a: Determine time delay of 1E and 3E modes regarding the terrestrial ground waves in frequency range between 0.7 and 1 MHz and distance in the range from 200 to 500 km.
b: What is the time delay for E and F modes of transmission for the given distance range?
c: What is the difference between time delay of 1F and 3F modes for the given distance range?

11. Find the Faraday rotation in ionosphere layer for $N_T = 5 \times 10^{17}$ el/m^2 in the following conditions: ($B_m = 5 \times 10^{-3}$ Wb/m^2)

a: LEO satellite radiowaves in 450 MHz.
b: GEO satellite radiowaves in 1.6 GHz.
c: HF radiowaves with frequency equal to 8.3 MHz.
d: Compare the obtained results with Fig. 4.14.

12. a: Determine the frequency range for an ionosphere layer with TEC$=10^{18}$ el/m^2 and Faraday rotation less 18°.

b: Estimate the Faraday rotation in the frequency range 1–3 GHz.

13. Repeat the Example 4.8 for frequencies between 1 and 3 GHz.

14. For $\Phi = 130^\circ$ and $|\lambda - \delta| = 40^\circ$ and solar zenith angle $\chi = 40^\circ$ at a location with latitude and longitude of 40° and $\theta = 30^\circ\ E$, respectively, find f_0E,f_0F, and maximum of solar zenith angle for F1 sub-layer ($R_{12} = 120$).

15. Repeat Example 4.11 for the year 1992.

Chapter 5
Propagation in 3 kHz to 30 MHz Band

5.1 Introduction

In the previous chapters, we considered the general concepts of radiowave propagation, especially in the troposphere and ionosphere. This chapter is dedicated to study of wave propagation in 3 kHz to 30 MHz frequency range, which is classified by ITU as VLF, LF, MF, and HF frequency bands.

These frequency bands were mostly used in the first days of radio industry, because of limited services and technologies. However, today with the increases in the service demands and quality, and with improvements in the radio technologies, new communication systems such as satellite systems, or line-of-sight radio systems, have taken their place. This chapter is organized as follows:

- Wave propagation in VLF/LF band
- Surface wave propagation
- Sky wave propagation in MF/HF band

5.1.1 Applications

Radiowave propagation in 3 kHz to 30 MHz frequency range has different applications in land, maritime, and aeronautical radiocommunications, such as:

- Navigational aids and radio determination systems
- Public audio broadcasting systems
- Fixed point-to-point communications
- Land, maritime, and aeronautical mobile radiocommunications
- Communications with marine and submarine vessels
- Military communications
- Standard frequency and time signal

A. Ghasemi et al., *Propagation Engineering in Wireless Communications*,
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- Amateur radio services
- Space research and operational services

The ITU frequency allocation tables include all services and dedicated frequency bands.

5.1.2 Evolution Trend

In the early twentieth century, because of limited electronic equipments and radio technologies, the foresaid applications were provided through LF, MF, and HF bands. Nowadays, based on technological advances in communication industry and especially satellite systems, most of these services are covered by satellites with better quality and wider range of services and applications, such as:

- International and regional satellite communications for fixed services
- VSAT networks
- Mobile satellite communication systems such as INMARSAT, mostly used in maritime mobile services
- Satellite broadcasting systems for regional, national, and local applications
- Global Positioning System, GPS

Therefore, communications in LF, MF, and HF frequency bands have lost their applications and are considered briefly in this book.

5.1.3 Main Considerations

Major consideration regarding radio systems with 3 kHz to 30 MHz frequency range are as follows:

- Limited capacity (mostly a single audio or data channel)
- Low quality of service due to interference and noise impairments
- Simple and fairly low-cost equipments
- Long-range communications based on the nature of surface waves and reflected waves from different ionosphere layers

Considering the wavelength of radiowaves, λ in the specified frequency band, i.e., 100 km to 10 m, antennas used in these systems have big dimensions with low gains such as:

- T-type antennas
- Inverted L-type antennas
- Logarithmic antennas with vertical and horizontal polarization
- Antennas
- Conical or inverted conical antennas
- Rhombic antennas

5.2 Propagation in VLF/LF Frequency Band

5.2.1 Introduction

This band includes 3–300 kHz frequency range with wavelengths of 1–100 km. Designing high-gain antennas is difficult because of their huge sizes. Radiowaves in this band are mostly used for ground waves, which are under the effect of the Earth electrical characteristics between the transmitter and the receiver, and can propagate through long distances.

5.2.2 Radiowave Propagation in Seawater

Communications through water in submarines are limited to the VLF (3–30 kHz) and even lower frequencies. This is because of the high attenuation caused by conductivity of seawater. In Fig. 5.1, σ and ϵ_r are given as a function of frequency.

Electric conductivity of seawater depends on impurity level and temperature. At frequencies less than 1 GHz, it can be calculated from:

$$\sigma = 0.18C^{0.93}[1 + 0.02(T - 20)]\,\mathrm{S/m} \tag{5.1}$$

VLF band can be used for short-range communications with submarine vessels.

In this equation, C is the impurity level and T is the temperature in degrees Celsius. In 20 °C, the electric conductivity is typically in the range 4–5 S/m, but it may be less than 1 S/m (like the Baltic Sea) or more than 6 S/m (like the Red Sea). The relative standard electric permittivity in 20 °C water is usually about 70–80. In Fig. 5.2 attenuation per meter is given at low frequencies (5–100 kHz).

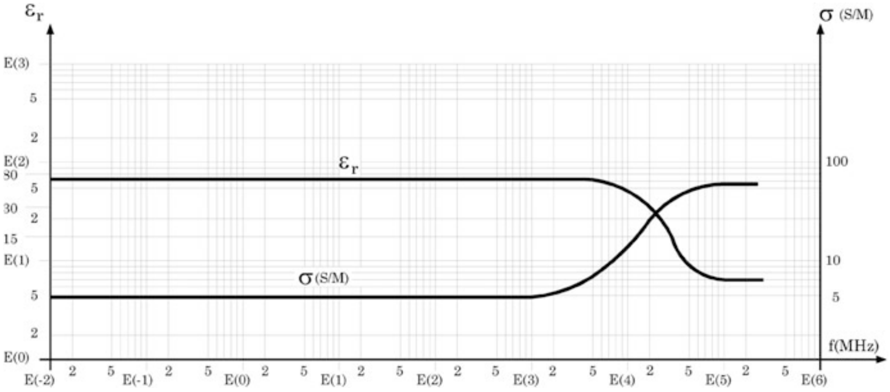

Fig. 5.1 Electrical characteristics of seawater (Ref.: ITU-R, P-527)

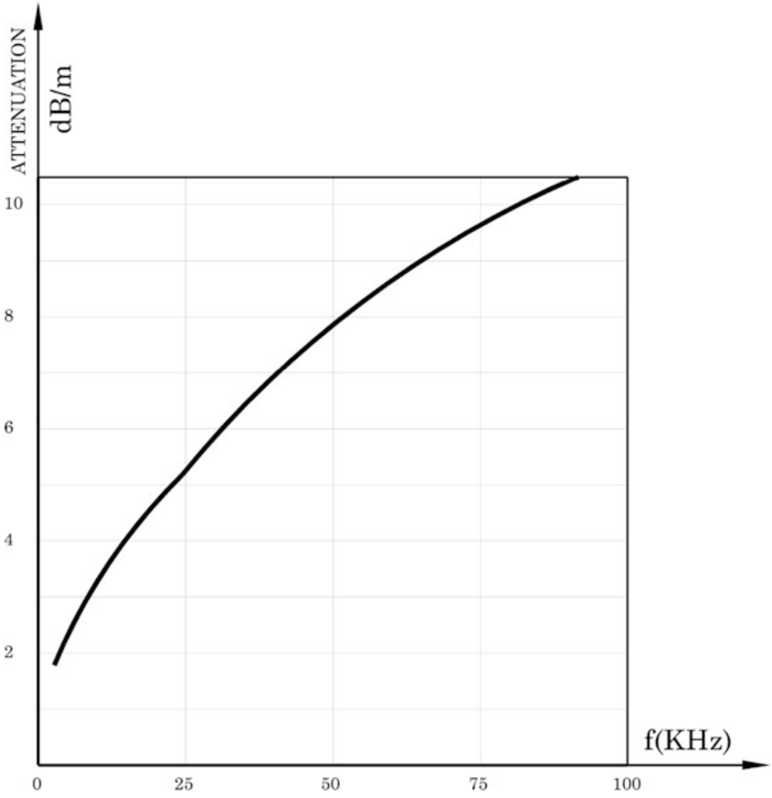

Fig. 5.2 Seawater attenuation

At lower frequencies, seawater acts as a lossy dielectric, and thus, the displacement current, $j\omega\epsilon E$, is much less than the conductive current σE, such that at frequencies less than 100 kHz, their ratio is about 10^{-4}. Then, the penetration depth of seawater is:

$$\delta_s = \sqrt{\frac{2}{\omega\mu_0\sigma}} \tag{5.2}$$

$$\delta_s(100\,\text{kHz}) = 0.8\,\text{m} \tag{5.3}$$

However, this quantity at frequencies around 10 kHz is about 2.5 m. Penetration of electromagnetic waves for one δ_s causes an attenuation of one Neper, 8.68 dB, so traveling a distance of 10–20 times the penetration depth will cause 87–174 dB attenuation.

5.2.3 Design Considerations

Parameters to be considered in designing radio systems for communications through seawater is completely different from those in the Earth atmosphere, because:

1. The radio signal enters the sea with some added radio noise. The noise temperature, with respect to the frequency band used, is about 10^{14} K. The signal level should be 20 dB higher than the noise level to make an appropriate reception possible. Since the water attenuates both the signal and noise in the same manner, therefore, the signal-to-noise ratio at the receiving antenna is almost 20 dB.

   If the receiver noise temperature is about 1000 K, and if the water attenuation is about 10^{-11}, the total noise temperature in the receiver will be around 2000 K, and the signal-to-noise ratio will be 3 dB less. This means that water will attenuate both the signal and noise strongly, while it will prevent further noise to be added to the signal.
2. The antennas used for undersea communications have large dimensions, because of the large wavelengths (10–100 km s) corresponding to the frequency band in use. Thus, the gain of these antennas is low since it is difficult to increase the antenna size, further.
3. The transmitted signals from underwater antennas to the air are strongly attenuated. This attenuation is about 100 dB for distances less than 20 m, and considering the low gains of the VLF antennas, very high-power transmitters are needed. For this reason, the submarine vessels have to come near the surface of the sea enabling them to communicate in an efficient manner.
4. Because of the considerable value of $\frac{\sigma}{\omega\epsilon}$ in water, the incoming and outgoing waves have a phase shift of 90° (to satisfy the electromagnetic boundary conditions). The radio waves from a horizontal antenna under the sea will travel horizontally in water but vertically in the air, as shown in Fig. 5.3.

   The minimum attenuation of surface waves over the sea, as the lossy radio waves over the land, happens in vertical polarization. This is why vertical

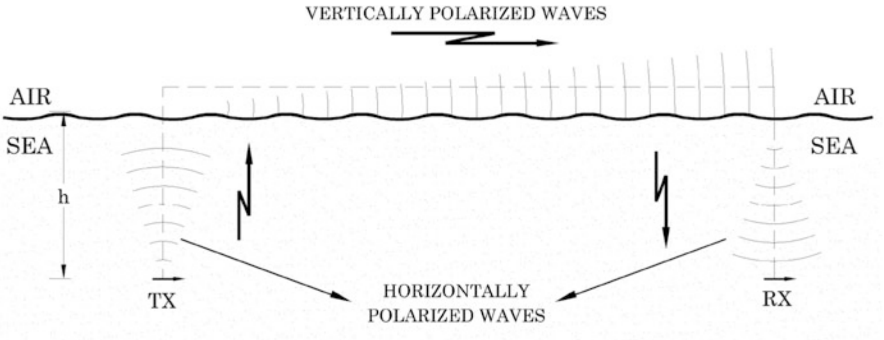

Fig. 5.3 Submarine vessel communications

antennas are usually used in land base stations to communicate with submarine units. High refraction of waves in the boundary of air and water will cause a stronger coupling of the waves to the vertical receiving antenna radiated from a submarine horizontally polarized antenna. From another perspective, a horizontally polarized wave propagating up to the surface of the sea will change into a vertically polarized wave because of the electromagnetic boundary conditions. Most of the concepts for the propagation of waves from an antenna in a lossless environment are not valid for lossy environments. For example, the integral of the Poynting vector over the surface of sphere with radius r is not equal to the whole energy propagated from the antenna (because of the lossy environment).

5. Major practical issues for design of radio systems are summarized below:
    - Low frequencies (VLF band) are usually used for this kind of communications.
    - The antenna should be located close to the water surface to the possible extent.
    - Using low frequencies, the length of the required antennas becomes usually around a few ten meters; and in spite of their large dimensions, the gain is very low.
    - For detecting the signal at the receiver, the transmitter power should be very high in the order of hundreds of kilowatts.

5.2.4 Submarine Vessel Radiocommunications

Radiowave communications among submarine vessels encounter a number of limitations such as using very low frequencies and high values of some parameters like penetration loss in seawater, size of antennas, sky noise penetrating inside water, and receiving noise temperature. The following case study is extracted from *Antennas and Radiowave Propagation*, R.E. Collin, including some realistic assumptions and technical calculation procedures.

Figure 5.4 shows a vertical monopole antenna transmitting to a submerged horizontal receiving antenna at a distance ρ. It will be assumed that the submerged vehicle antenna is an insulated wire of length l equal to 25 m. The transmitting antenna is assumed to be a monopole of length L. The frequency is very low in order to avoid prohibitive attenuation in the sea. Thus both l and L are very small relative to a free-space wavelength. Under these conditions, the current distribution on the antennas can be taken as triangular, as shown in Fig. 5.4.

The received open-circuit voltage V_{oc} is given by:

$$V_{\mathrm{oc}} = -\frac{1}{I_0}\int_0^L I(z)E_z(z)dz \tag{5.4}$$

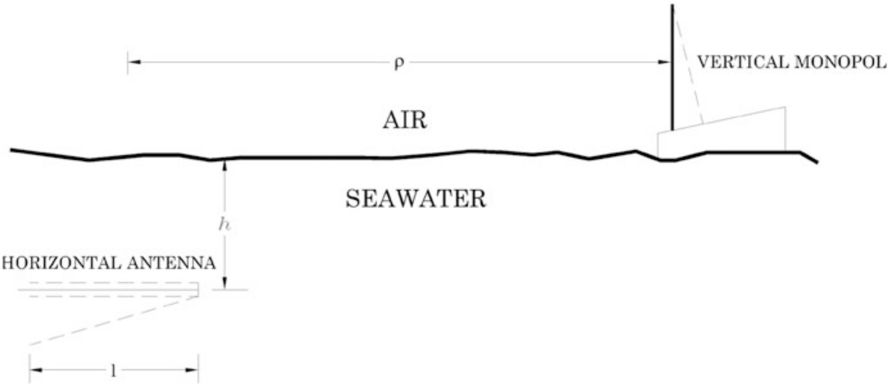

Fig. 5.4 Submarine to shore radio link

where $I(z)$ is the current on the transmitting antenna and $E_z(z)$ is the field radiated by the wire antenna of length l when it is used for transmitting with an input current I_0. By using suitable expression for $E_z(z)$ as follows:

$$E_z = \frac{jk_0 z_0 I dl}{2\pi\rho} \times \frac{\gamma_0}{\gamma_1} F(\rho) e^{-\gamma_0\rho - \gamma_1 h \cdot \cos\phi} \tag{5.5}$$

And assuming triangular current distributions, we obtain:

$$V_{\text{oc}} = \frac{jk_0 Z_0 I_0 l}{4\pi\rho I_0} \times \frac{I_{\text{in}} L}{2} \times \frac{\gamma_0}{\gamma_1} e^{-\gamma_1 h - \gamma_0 \rho} \tag{5.6}$$

$$|V_{\text{oc}}| = \frac{K_0^2 Z_0 l L \delta_s}{8\sqrt{2}\pi\rho} e^{-h/\delta_s} I_{\text{in}} \tag{5.7}$$

When the receiving antenna is matched to its load termination, that is, $Z_L = Z_{\text{in}}^*$, the received power will be $P_r = |V_{\text{oc}}|^2/4R_{\text{in}}$, where R_{in} is the input resistance of the receiving antenna.

In order to determine the signal-to-noise ratio at the receiver input, the contribution of the lossy sea at temperature T_1 and the atmospheric noise at temperature T_2 to the received noise must be found. The atmospheric noise and the sea noise are uncorrelated, so the received noise from these two sources may be added together. When the antenna is submerged to a depth of a few meters, the power it would radiate is almost entirely absorbed in the seawater. The principle of detailed balancing then shows that the antenna-noise temperature due to the lossy sea is T_1. The error made in using this assumption is negligible if the path attenuation up to the surface is greater than 20 dB. Even for an attenuation of 10 dB, the error is no greater than 10 %.

The contribution of the atmospheric noise to the received noise can be determined approximately on a comparative basis. When the antenna is located in free space, it would have an antenna-noise temperature equal to T_2. The noise-like electromagnetic field incident on the air-sea interface from all directions above the sea is partially reflected at the surface. The remainder is transmitted down to the antenna and undergoes considerable attenuation in the process. The minimum reflection coefficient at normal incidence is:

$$\Gamma = \frac{(j\omega\mu_0/\sigma)^{1/2} - Z_0}{(j\omega\mu_0/\sigma)^{1/2} + Z_0} \approx -1 + 2\frac{(j\omega\mu_0/\sigma)^{1/2}}{Z_0} \tag{5.8}$$

The transmission coefficient is $1 + \Gamma \approx 2(j\omega\mu_0/\sigma)^{1/2}/Z_0 = 2(j\omega\epsilon_0/\sigma)^{1/2}$. The power transmission coefficient is $4\omega\epsilon_0/\sigma$. The least amount of attenuation of the noise-field power incident on the receiving antenna is $4(\omega\epsilon_0/\sigma)e^{-2h/\delta_s}$. Thus the maximum possible contribution to the antenna-noise temperature from atmospheric noise is:

$$T_2' = 4T_2\left(\frac{\omega\epsilon_0}{\sigma}\right)E^{-2h/\delta_s} \tag{5.9}$$

The effective antenna-noise temperature T_A equals $T_1 + T_2'$. In the VLF band, T_2 is of order 10^{14} K, while T_1 is close to 273 K. If the total attenuation due to the low interface coupling and high path attenuation exceeds 120 dB, then atmospheric noise can be neglected. A more accurate expression for the noise temperature contributed by the atmospheric noise field would require a consideration of the integrated effect of all the incident noise fields over all angles.

If we assume that $f = 50\,\text{kHz}$, $h = 10\,\text{m}$, and $T_2 = 10^{14}\,\text{K}$, then we find $T_2' = 23.2\,\text{K}$, which is negligible.

In order to proceed further with the evaluation of this communication link, we must know the input resistance of the receiving antenna and the properties of the transmitting antenna. An insulated wire submerged in seawater may be viewed as a length of open-circuited lossy coaxial transmission line. On this basis, its input impedance may be calculated. When $l \ll \lambda_0$, then:

$$R_{\text{in}} = \frac{40\alpha\beta l}{\epsilon_r k_0}\ln\frac{b}{a} \tag{5.10}$$

$$R_{\text{in}} = \frac{-60}{\epsilon_r k_0 l}\ln\frac{b}{a} \tag{5.11}$$

Where α and β are the attenuation and phase constants for the current wave on the insulated wire, a is the wire radius, b is the outer radius of the insulator, and ϵ_r is the dielectric constant of the insulator. If we assume that the antenna is made from 50 Ω coaxial cable by removing the outer conductor and $\beta = 3.5\sqrt{\epsilon_r}k_0$, $\alpha = 0.09\sqrt{\epsilon_r}k_0$. Thus if we also use $\epsilon_r = 2.56$ we get

$$R_{\text{in}} = 105.5\ (l/\lambda_0) \tag{5.12}$$

$$X_{\text{in}} = -4.97\ (\lambda_0/l) \tag{5.13}$$

Note that R_{in} is very small and X_{in} is very large.

The above antenna requires an inductance of $0.066\ (\lambda_0/l)^2\ \mu\text{H}$ to tune it to resonance. For an unloaded bandwidth of 300 Hz, the coil Q should be $50000/300 = 167$, and thus the coil resistance will be $R_c = (\omega L/Q) - R_{\text{in}} \approx 7.14\,\Omega$, which is much larger than R_{in} when $l = 25$ m and $\lambda_0 = 6$ km.

If the inductor is considered to be part of the antenna and the receiver is matched to $R_{\text{in}} + R_c = R$, then R must be used in place of R_{in} in the expression for received power to give:

$$P_r = \frac{|V_{\text{oc}}|^2}{4R} \tag{5.14}$$

The loaded bandwidth of the receiver input circuit will be 600 Hz.

When the receiver noise figure is F_n and the coil resistance is assumed to be at the temperature T_1, the total noise referred to the receiver input will be:

$$\begin{aligned} P_n &= (F_n - 1)KT_0\Delta f + k\Delta f\left(\frac{R_{\text{in}}(T_2' + T_1)}{R} + \frac{R_c T_1}{R}\right) \\ &= (F_n - 1)KT_0\Delta f + kT_1\Delta f - k\Delta f\frac{R_{\text{in}}}{R}T_2' \\ &\approx (F_n - 1)KT_0\Delta f + kT_1\Delta f \end{aligned} \tag{5.15}$$

For $F_n = 4,\ \Delta f = 600$ Hz, and $T_1 = 273$ K, we obtain $P_n = 9.71 \times 10^{-18}$ W.

The transmitting antenna input current will be found by assuming that the required signal-to-noise ratio is 10. By using Eq. (5.7), the expression for P_r, and Eq. (5.13), we find that:

$$I_{\text{in}} = \frac{2 \times (80RP_n)^{1/2}\lambda_0^2\rho e^{h/\delta_s}}{\pi Z_0 lL\delta_s} \tag{5.16}$$

For a bandwidth of 600 Hz, $l = L = 25$ m, $h = 12$ m, $\rho = 10$ km, and with the previously assumed parameters, we obtain $I_{\text{in}} = 4.6 \times 10^3$ A. Clearly this large input current cannot be realized very easily in practice. The large interface coupling loss (61.58 dB) and the depth attenuation loss (76.85 dB) increase the required input current by a factor of 8.35×10^6. Without this loss, an input current of 0.55 MA would have sufficed.

The radiation resistance of a short monopole antenna is given by:

$$R_a = 40\pi^2\left(\frac{L}{\lambda_0}\right)^2 \tag{5.17}$$

The antenna will also exhibit a large input capacitive reactance. This reactance will depend on the diameter-to-length ratio of the monopole. An antenna with a large cross section will have a smaller reactance. An inductance is normally used to tune the antenna to resonance, and the antenna current is determined by the series resistance of this tuning coil when the radiation resistance is very small. This also means that the tuning coil must dissipate close to 100 % of the transmitter power output, and the overall efficiency will be low.

If the antenna has an effective cross-sectional diameter d, the approximate value of the input reactance is:

$$X_{\text{in}} = -\frac{30}{\pi}\frac{\lambda_0}{L}\left(\ln\frac{4L}{d} - 1\right) \tag{5.18}$$

The antenna is assumed to be tuned to the resonance, with a base loading coil with loaded quality factor Q and total series resistance $2R$. (This includes the generator resistance R_g, which we choose equal to R.) The tuning coil must provide an equal and opposite reactance. For a bandwidth of 600 Hz, the loaded Q should be $f/600$, and the total series resistance $2R$ is given by $-X_{\text{in}}/Q$ or:

$$2R = \frac{-X_{\text{in}}}{f}600 \tag{5.19}$$

The efficiency is $R_a/(R + R_a) \approx R_a/R$ and is given by:

$$\eta = \frac{80\pi^3}{60[\ln(4L/d) - 1]}\frac{f}{300}\left(\frac{L}{\lambda_0}\right)^2 \tag{5.20}$$

If we use $L = 25\,\text{m}$, then $R_a = 6.85 \times 10^{-3}\,\Omega$. For $d = 1\,\text{m}$, $\eta = 1.382 \times 10^{-4}$, which is very small. The power in R_a is $I_{\text{in}}^2 R_a = 1.45 \times 10^5$, and the input power is a factor η^{-1} larger, or 1.04×10^9 W. This is a very unrealistic power level. The example has shown the great difficulty that exists in providing communication to a submerged antenna. The high attenuation of seawater requires the use of very low frequencies, and if the antennas are short in terms of the very large wavelength, they are very inefficient; the result is a requirement of unrealistically large transmitter power.

If the frequency is reduced to 10 kHz, the interface coupling loss increases by 7 dB, but the depth attenuation decreases by a factor of 43.7 dB for a net gain of 36.7 dB. However, the antennas' efficiencies would decrease by a significant amount unless their lengths are increased by a factor of 5. Consequently the use of lower frequencies helps, but the antenna size requirement remains a challenging problem.

5.2.5 Propagation in the Earth Atmosphere

Wave propagation in the air mostly contains surface waves in low frequencies of VLF/LF band and ground waves at higher frequencies. Surface/ground wave propagation characteristics and relative figures will be explained in the next sections.

5.3 Surface Wave Propagation

5.3.1 Introduction

Surface waves generally consist of low frequencies which are about several kilohertz to several megahertz, normally in the range of 3 kHz to 3 MHz. At low frequencies, land and air will make an atmospheric waveguide which is used to conduct the wave in this band. Surface waves and space waves (including direct and reflected waves) together is called ground waves. While placing the antenna at the heights $h > 10\lambda$ above ground surface, by increasing the height, surface waves component will decrease and it will be more similar to space waves. In contrast, by decreasing the antenna height and placing it near the ground surface, the main component of wave becomes surface waves. Propagation of surface waves is the main part of propagation in this band. The signal attenuation between the transmitter and receiver will have the reverse relation with forth power of distance. In this case, antennas should be installed on high towers, like voice broadcasting radio transmitter with strong power between 10 kW to 1 MW which could broadcast waves to several kilometers.

5.3.2 Electric Characteristics

Ground wave propagation is mostly affected by the Earth electric characteristics, lower layer of atmosphere, and wave penetration depth. Transmission media and wave propagation electric parameters consist of the three following major factors:

- Electric permittivity
- Magnetic permeability
- Electric conductivity

For more information, several figures and data about the dielectric coefficient, electric conductivity, and radiowave penetration depth in the Earth are presented in this chapter.

5.3.3 Electric Characteristic Variation

In this section, several figures are presented to show the variation in the Earth electric characteristics versus frequency. These figures are extracted from ITU-R, P.527-3 recommendation. Each category consists of eight curves which are introduced here:

A: Seawater	B: Wet ground
C: Fresh water	D: Dry ground

E: Completely dry ground F: Pure waterproof
G(−1): −1° ice G(−10): −10° ice

- **Electric Permittivity**

  Relative permittivity of each medium is given by the following equation:

$$\epsilon = \epsilon_r \cdot \epsilon_0, \qquad \epsilon_0 = \frac{1}{36\pi} \times 10^{-9}\,\mathrm{F/m} \tag{5.21}$$

  Figure 5.5 shows the electric permittivity(dielectric constant) variations for different kinds of ground versus frequency. As indicated, this coefficient is in the range of 3–80.

- **Magnetic Permeability**

  Relative permeability of each medium is given by the following equation:

$$\mu = \mu_r \cdot \mu_0, \qquad \mu_0 = 4\pi \times 10^{-7}\,\mathrm{H/m} \tag{5.22}$$

  The value of μ_r for different types of ground is usually about 1.

- **Electric Conductivity**

  Ground electric conductivity is one of the most important parameters in waves transmission and attenuation. It has a reverse relation with wave penetration depth, i.e., as electric conductivity is increased, the wave penetration depth decreases and the wave attenuates more rapidly. Figure 5.6 shows the variations of electric conductivity for different kinds of ground in a logarithmic scale.

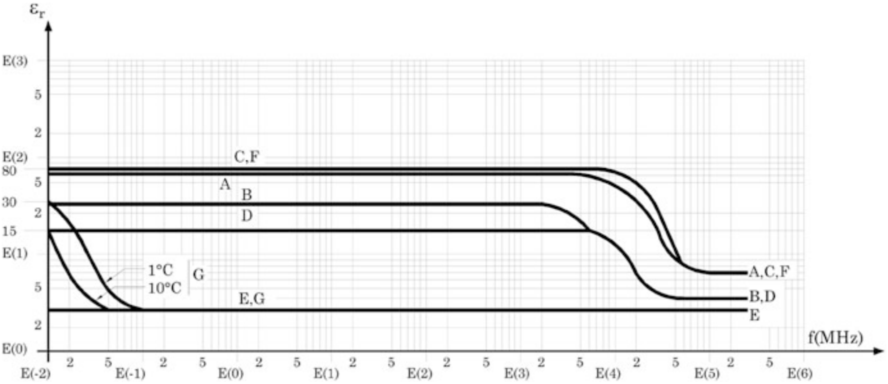

Fig. 5.5 Variation of dielectric constant vs. frequency

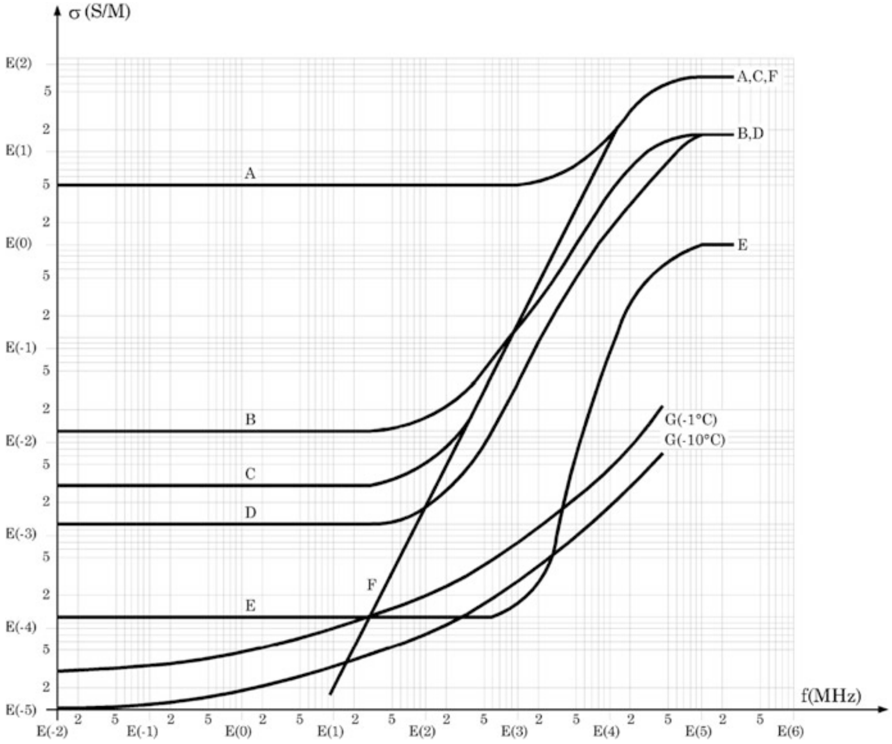

Fig. 5.6 Variation of conductivity vs. frequency

5.3.4 Wave Penetration

Earth electric parameters usually change with the depth abruptly. The penetration depth plays an important role in determining whether lower layers influence wave propagation or not.

Penetration depth, denoted by δ, depends on the material and the frequency of propagating wave. It is the depth at which the amplitude of the propagating wave reaches to $1/e$ (equal to 0.37 %) of its initial amplitude as it enters the layer.

Figure 3.31 of Chap. 3 shows the penetration depth as a function of frequency for different ground materials in which the following points can be concluded:

- When the penetration depth is less than the first layer thickness, the underlying layers have little effect on propagation of ground waves, but when the penetration depth is much higher than the thickness of the first layer, wave propagation is affected by the electric parameters of the subsequent layers.
- When the layers are thin in comparison with the penetration depth, the average value for ϵ_r and σ should be considered in the calculations.

- When radio waves are incident to the water surface, they reflect in many directions; thus, the electric parameters of the nearby surfaces should be considered too. No standard range is available for this phenomenon, but some technical references consider the first Fresnel zone.

Example 5.1. Considering Figs. 5.5 and 5.6, find the fluctuations of ϵ_r and σ for wet and dry grounds in frequency range of 10 kHz to 10 GHz.

Solution. Using the curves B, D, and E in the mentioned diagrams, it is concluded that:

$$\begin{aligned} &10\,\text{kHz} < f < 30\,\text{MHz} \quad \rightarrow 3 < \epsilon_r < 30, 10^{-4} < \sigma < 10^{-2} \\ &30\,\text{kHz} < f < 10\,\text{GHz} \quad \rightarrow 3 < \epsilon_r < 30, 10^{-4} < \sigma < 4 \end{aligned}$$

■

5.3.5 *Effective Factors in Electric Characteristics*

Electric characteristics of the Earth depend on different factors, such as:

- **Soil Properties**
  Different components of the soil change the ϵ_r and σ, but the fluctuations of moisture is much more effective.
- **Moisture**
  Moisture is the most important factor in determining electric parameters. Experiments show that increasing the moisture will increase both ϵ_r and σ. For example, the electric conductivity of dry land is about 0.0001 S/m, but with ordinary moist, it increases to 0.01 S/m. This can also be interpreted from the curves, B, D, and E in Figs. 5.5 and 5.6.
- **Temperature**
  Experiments show that at low frequencies, the electric conductivity changes 3 % per 1 °C, but fluctuations in ϵ_r are negligible. However, in temperatures near the freezing temperature, both of these parameters are decreased strongly. Considering the fluctuations of the temperature during the year, and its fast decrease in deeper layers of the Earth, its effect at higher frequencies should be considered. Moreover, the change of water to ice has severe effects on the electrical parameters.
- **Energy Absorption**
  Different objects on the Earth influence the energy absorption of the radiowaves. These effects are not direct and should be considered approximately in calculations.

5.3.6 Received Power

In propagation of surface waves, the received power at the receiving end can be expressed as follows:

$$P_r = P_d \cdot |2A_s|^2 \tag{5.23}$$

where:

P_r: Received power from surface waves
P_d: Received power from direct waves
A_s: Attenuation factor for surface waves

As mentioned in Chap. 1, P_d is calculated from the following equation, which is actually related to the free-space attenuation of waves:

$$P_d = P_t \cdot G_t \cdot G_r \cdot \lambda^2/(4\pi d)^2 \tag{5.24}$$

Thus, the key factor for calculation of received power is to find A_s in a proper manner. In the above equation, P_t is the transmitting power with a similar unit to P_d. G_r and G_t are the gains of the transmitting and receiving antennas, respectively.

5.3.7 Vertically Polarized Waves

The propagation of vertically polarized waves was solved in the beginning of the twentieth century by Sommerfeld. With some approximations, the attenuation function for this case is given by:

$$A_s = F = 1 - j\sqrt{\pi\,\Omega} \cdot e^{-\Omega} \cdot \operatorname{erfc}(j\sqrt{\Omega}) \tag{5.25}$$

$$\omega = p\,e^{-jb} \tag{5.26}$$

In the last equation, p is the numerical distance and b is the argument of the parameter Ω. p and b can be determined by:

$$p = \frac{Kd}{2\sqrt{\epsilon_r^2 + (\sigma/\omega\epsilon_0)^2}} \tag{5.27}$$

$$b = \arctan\left(\frac{\epsilon_r\,\epsilon_0\,\omega}{\sigma}\right) \tag{5.28}$$

$$\frac{\sigma}{\omega\,\epsilon_0} = \frac{1.8 \times 10^4 \times \sigma}{f(\mathrm{MHz})} \tag{5.29}$$

After calculating p, the following figures are used to determine $|A_s|$:

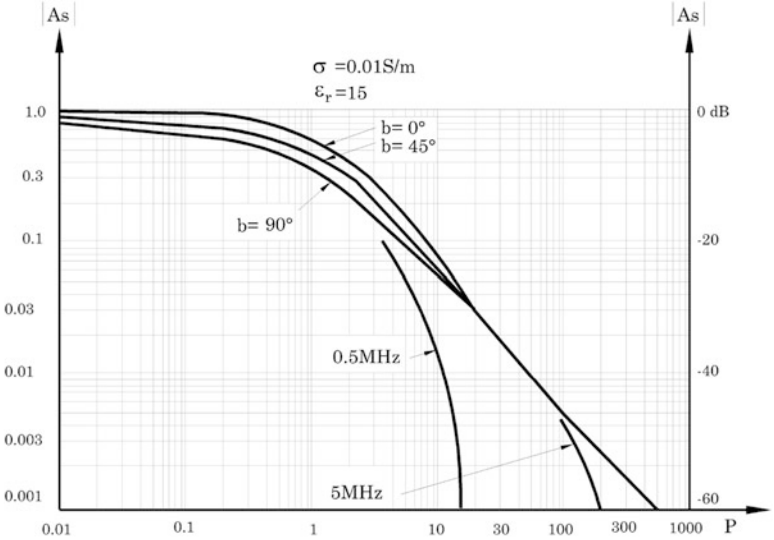

Fig. 5.7 Surface wave attenuation over flat Earth ($|A_s|$ vs. p) ($\sigma = 0.01$ S/m and $\epsilon_r = 15$, Full Logarithmic Scales)

- Figure 5.7: Flat Earth surface wave attenuation $|A_s|$ versus the numerical distance p for 0.5 MHz up to and 5 MHz frequency
- Figure 5.8: Spherical Earth surface wave attenuation $|A_s|$ versus the numerical distance for 0.5 MHz up to and 5 MHz frequency, $\epsilon_r = 15$ and $\sigma = 10^{-2}\ \mathrm{S/m}$

To use Fig. 5.7 for flat ground, the distance between the transmitter and the receiver must be less than:

$$d_f\ [m_i] = \frac{50}{\sqrt[3]{f[\mathrm{MHz}]}} \tag{5.30}$$

In this equation, d_f is the maximum distance in mile for which the flat Earth curves can be used, and f is the frequency of the waves in MHz. For distances greater than d_f, the attenuation will be higher and the curves of Fig. 5.8 should be used.

For $b \leq 90°$, $|A_s|$ is given by:

$$|A_s| = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sqrt{\frac{p}{2}} \cdot e^{-0.6p} \cdot \sin(b) \tag{5.31}$$

In the specified frequency range (3 kHz to 3 MHz), the noise in cities is so high that the signal level at the receiving antenna should be between 1 and 19 mV/m, but in rural areas this value can be lower. If the receiving antenna is very close to ground surface, the power of the surface wave is $|2A_s|^2$ times higher than the corresponding

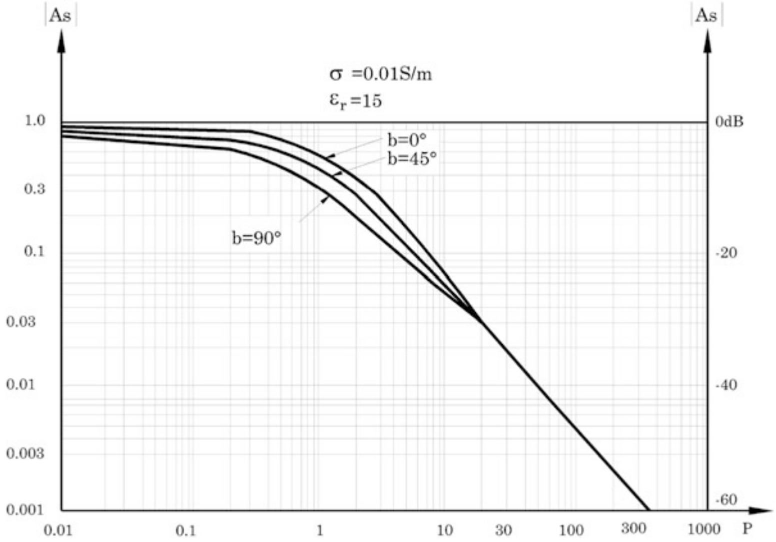

Fig. 5.8 Surface wave attenuation over spherical Earth ($|A_s|$ vs. p) ($\sigma = 0.01$ S/m and $\epsilon_r = 15$, Full Logarithmic Scales)

value for free-space wave, as shown in Eq. (5.23). This important feature is used to determine the range of antennas located close to ground, in low and medium frequencies.

$$|E_r| = |E_t| \cdot |2A_s| \tag{5.32}$$

5.3.8 Horizontally Polarized Waves

In this case, the parameters p and b are given by:

$$p = \frac{\pi d}{\lambda_0} \times \frac{1.8 \times 10^4 \sigma}{f(\text{MHz})} \times \frac{1}{\cos b} \tag{5.33}$$

$$b = \tan^{-1} \frac{(K' - 1)\omega\epsilon_0}{\sigma} \tag{5.34}$$

$$\epsilon_r = K' - 1 \tag{5.35}$$

Figures 5.7 and 5.8 are also used in this case. Note that for horizontally polarized waves, the value of p for the same distance is much greater than vertically polarized waves. Thus, the attenuation of horizontal waves is greater than the vertical waves.

Example 5.2. At frequency $f = 5\,\text{MHz}$ and ground characteristics of $\epsilon_r = 15$ and $\sigma = 0.01$ for vertically polarized waves, find attenuation factor at 80 km away from the transmitter.

Solution.

$$d_f = 50/\sqrt[3]{5} = 29.24\,mi$$

Since $d > d_f$ then the curves of Fig. 5.8 must be used. First we calculate p:

$$\lambda = \frac{C}{f} = \frac{3 \times 10^8}{5 \times 10^6} = 60\,\text{m}$$

$$p = \pi d/\lambda \sqrt{\epsilon_r^2 + (\sigma/\omega\epsilon)^2} \approx 107$$

Since $p > 20$, there is no need to calculate b, and from Fig. 5.8, it concludes:

$$p = 107 \quad \Rightarrow \quad |A_s| = 0.05$$

■

5.3.9 ITU-R Diagrams

As stated before, surface waves, line-of-sight waves, and reflected waves altogether are known as ground waves. These waves are important in the frequency band of 10 kHz to 30 MHz. In fact, in radiocommunications, surface waves are more important when the antennas are located close to the ground, but when they are located at higher positions, especially at heights more than ten times of the corresponding wavelength, the line-of-sight and reflection components have a stronger effect.

For calculating the signal level at the receiving end, ITU has prepared several applied diagrams from which two examples are given below.

- Figures 5.9 and 5.10 for homogeneous paths (constant σ and ϵ_r), in frequency range of 10 kHz to 30 MHz.
- Figures 5.11 and 5.12 for inhomogeneous paths (constant frequency) and variable ϵ_r and σ

The reader is referred to ITU-R, P.368 for more curves and details.

Because of the complexity of the calculations for ground waves, a software named GRWAVE, is produced by ITU-R. The following points should be considered when using these diagrams:

- The frequency range is 10 kHz to 30 MHz.
- The curves can be used for ground waves by neglecting the ionospheric waves.

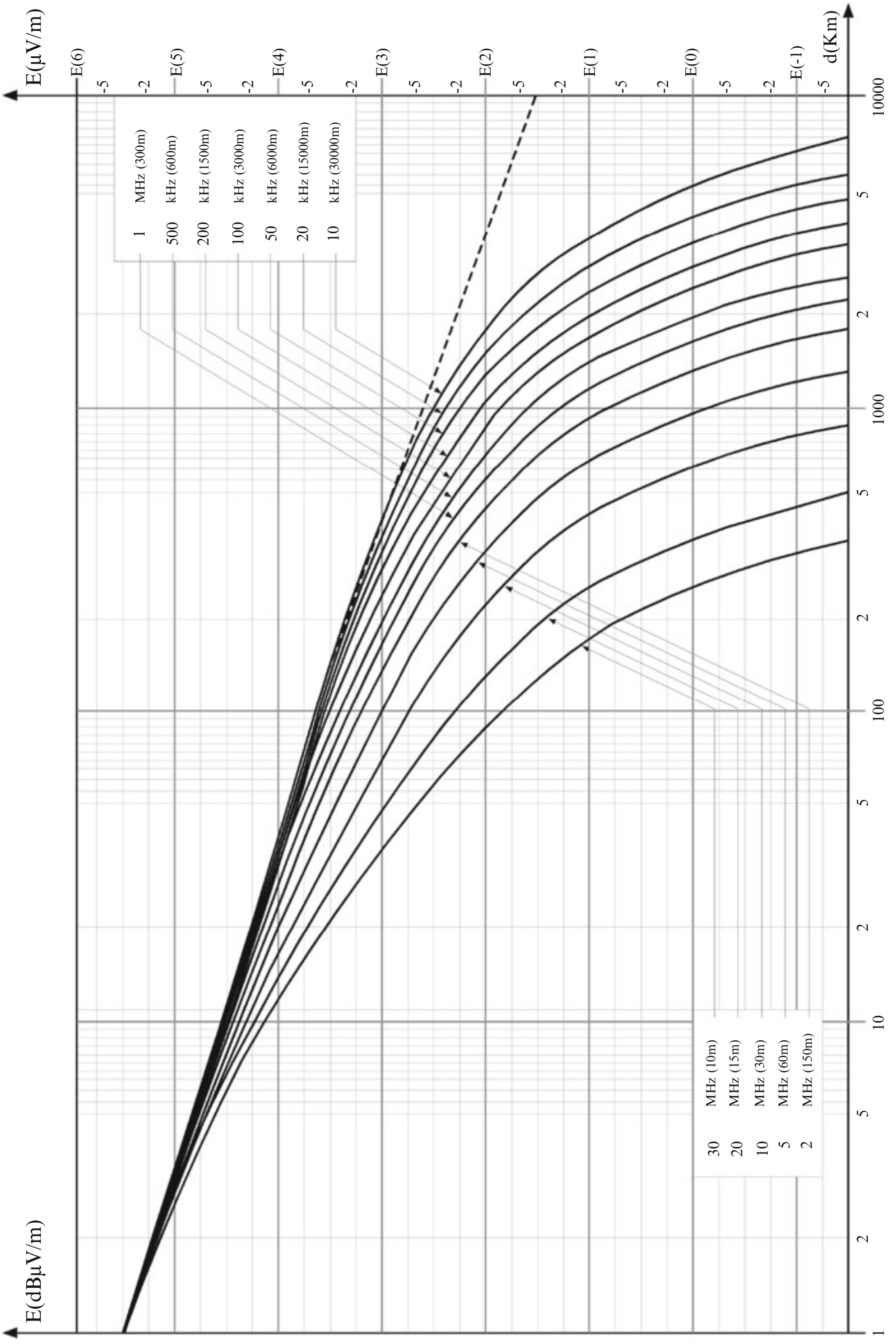

Fig. 5.9 Ground wave curves, seawater $\sigma = 5\,\mathrm{S/m}$, $\epsilon_r = 70$ (Ref.: ITU-R, P-368)

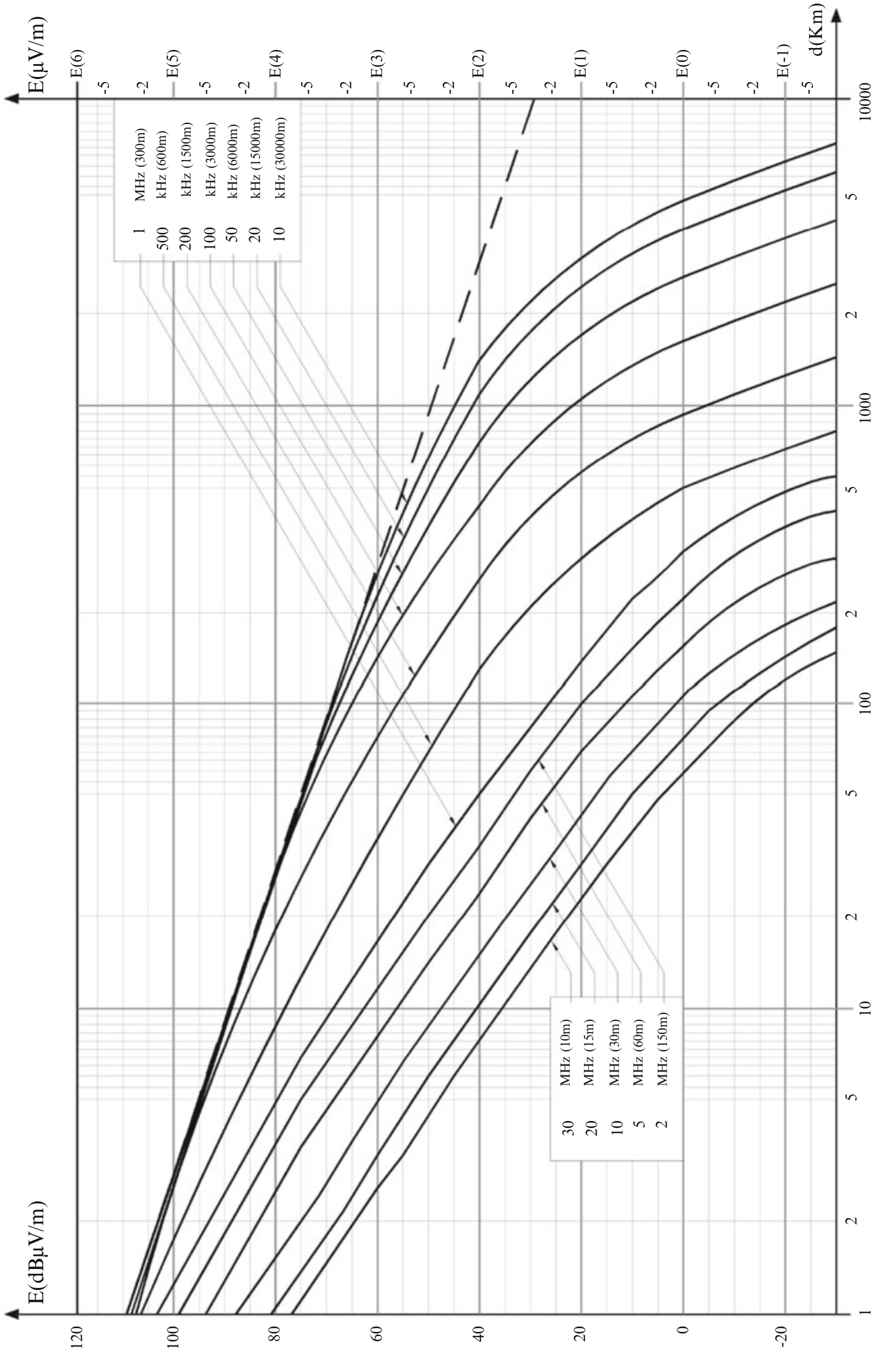

Fig. 5.10 Ground wave curves, dry land $\sigma = 0.001\,\text{S/m}$, $\epsilon_r = 15$ (Ref.: ITU-R, P-368)

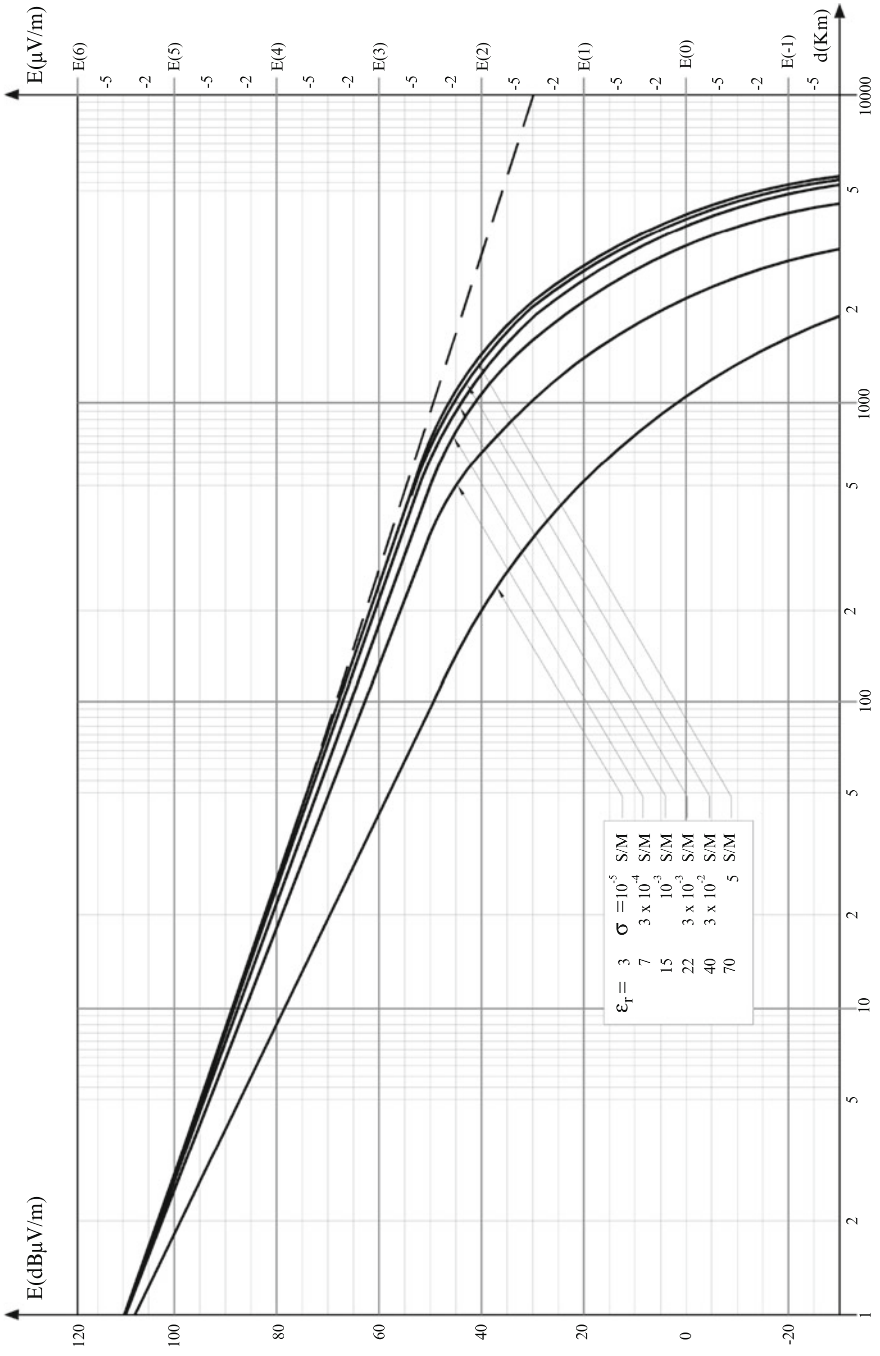

Fig. 5.11 Ground wave curves at 30 kHz (Ref.: ITU-R, P-368)

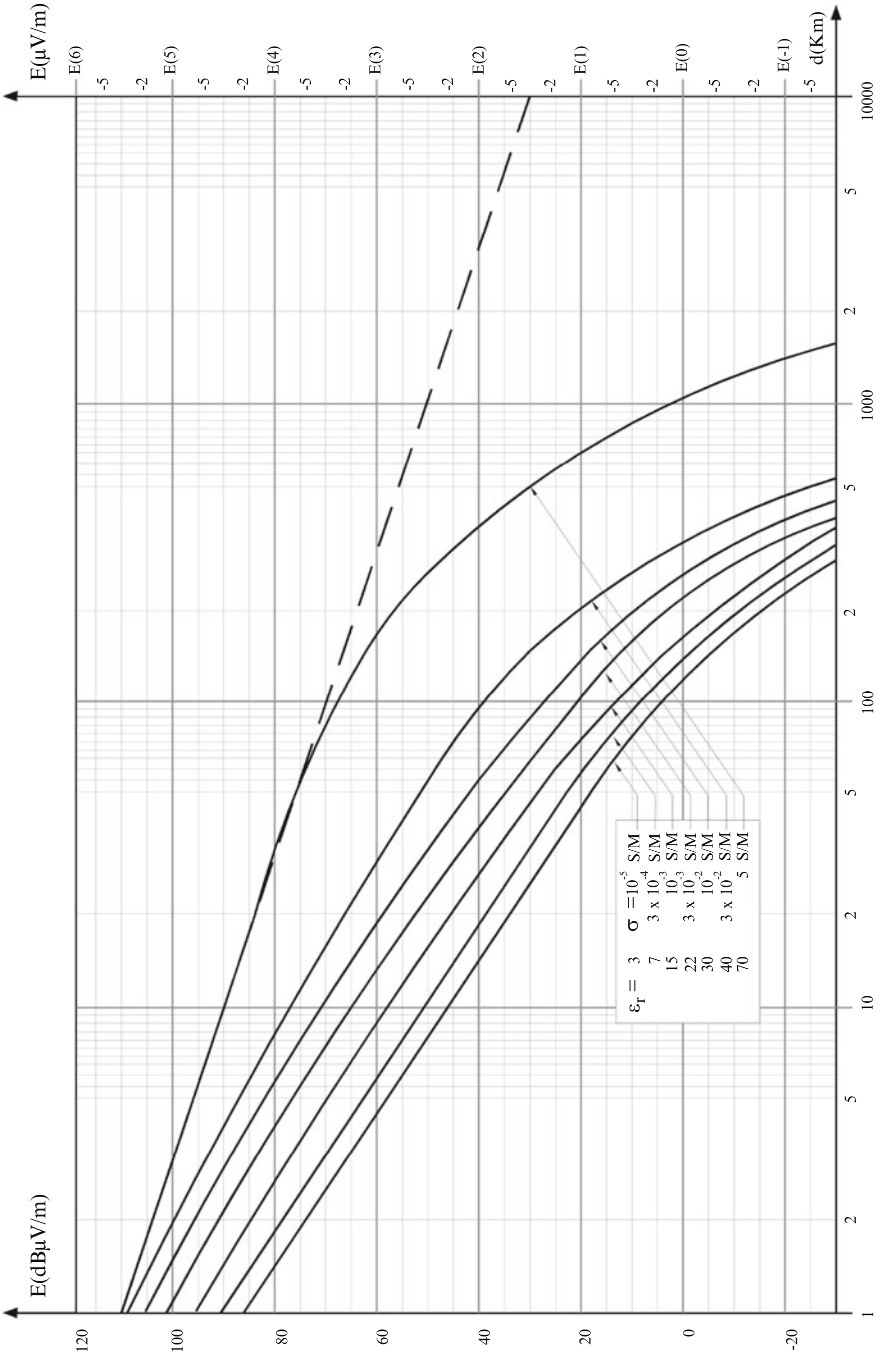

Fig. 5.12 Ground wave propagation curves at 30 MHz (Ref.: ITU-R, P-368)

- The curves should not be used where receiving antenna is located well above the Earth surface.
- Assuming that $\epsilon_r << 60\lambda\sigma$, these curves can be used for antenna heights less than $h = 1.2\,\sigma^{1/2} \cdot \lambda^{3/2}$.
- Both TX and RX antennas are located at the ground level.
- The transmitting unit is small monopole vertically oriented on a perfect conductor ground.
- The transmitter power is 1 kW, and the corresponding electric field intensity 1 km away would be 300 mV/m
- These curves are based on spherical distances from the Earth.
- In these curves, the vertical component of the electric field is given, which can be measured at a far location.

The basic loss in ground waves is given by:

$$L_b[\text{dB}] = 137.2 + 20\log f - E \tag{5.36}$$

In this equation, parameters and the related units are as follows:

f: Frequency in MHz
E: Electric field intensity in dB (μV/m), which can be derived from the mentioned diagrams.

Example 5.3. A transmitting antenna with 200 W output power at f = 10 MHz is vertically placed close to the ground. The parameters of the ground at a distance of 30 km are $\epsilon_r = 10$ and $\sigma = 0.005\,\text{S/m}$. If the gains of transmitting and receiving antennas are unity, determine the received signal power.

Solution.

$$\lambda = \frac{C}{f} = 30\,\text{m}$$

$$P = \pi d'/\lambda \sqrt{\epsilon_r^2 + (\sigma/\omega\epsilon)^2} \approx 233$$

$$b = \arctan\left(\frac{\epsilon_r\epsilon_0\omega}{\sigma}\right) = \arctan(1.11) \approx 48^\circ$$

and by using (5.31):

$$|A_s| = \frac{2 + 0.3P}{2 + P + 0.6P^2} - \sqrt{\frac{P}{2}} \cdot e^{-0.6P} \sin b = 2.146 \times 10^3$$

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi d)^2} \times |2A_s|^2 \approx 2.34 \times 10^{-9}\,\text{W} = 2.34\,\text{nW}$$

■

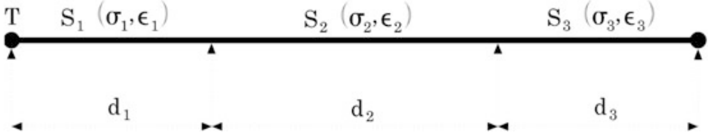

Fig. 5.13 Mixed path in ground wave link

5.3.10 Mixed Paths

The ground wave curves can be used to determine the field strength of waves propagating through mixed paths. There are many methods to solve this problem. One of the oldest and most effective one is the Millington method, which is explained below.

In Fig. 5.13, the distance between the transmitter and the receiver is composed of three segments with lengths of d_1, d_2, and d_3. Each segment is homogeneous in its region. Field strength can be calculated from the foresaid curves. At a specific frequency, first the corresponding curve for the segment S_1 is determined to calculate $E_1(d_1)$. Then, the similar procedure shall be followed for segment S_2 to indicate $E_2(d_1)$ and $E_2(d_1 + d_2)$, and finally $E_3(d_1 + d_2)$ and $E_3(d_1 + d_2 + d_3)$ shall be determined. Therefore:

$$E_TR = E_1(d_1) - E_2(d_1) + E_2(d_1 + d_2) - E_3(d_1 + d_2) + E_3(d_1 + d_2 + d_3) \qquad (5.37)$$

Applying the same procedure once more along with interchanging the transmitter and the receiver, E_RT can be calculated from the following expression:

$$E_RT = E_3(d_3) - E_2(d_3) + E_2(d_3 + d_2) - E_1(d_3 + d_2) + E_1(d_3 + d_2 + d_1) \qquad (5.38)$$

Finally the field strength at the receiving end is found to be:

$$E_R = (E_TR + E_RT)/2 \qquad (5.39)$$

Example 5.4. Radiowaves with transmitting power of 100 W at frequency of 500 kHz are propagated in a path composed of three segments with the following parameters:

$S_1 : d_1 = 20\,\text{km}, \sigma_1 = 0.001\,\text{S/m}, \epsilon_1 = 15$
$S_2 : d_2 = 10\,\text{km}, \sigma_2 = 5\,\text{S/m}, \epsilon_2 = 70$
$S_3 : d_3 = 50\,\text{km}, \sigma_2 = 0.001\,\text{S/m}, \epsilon_3 = 15$

1. Determine the electric field strength at the receiving end.
2. Determine the basic loss of the path.

Solution. 1. Using the corresponding curves for the 1 kW wave, yield:

$$\begin{gathered}
S_1 : (\text{Fig. } 5.10) \Rightarrow E_1(d_1) = E_1(20) = 68\,\text{dB}(\mu\text{V/m}) \\
S_2 : (\text{Fig. } 5.9) \Rightarrow E_2(d_1) = E_2(20) = 85, \\
E_2(d_1 + d_2) = E_2(30) = 80\,\text{dB}(\mu\text{V/m}) \\
S_3 : (\text{Fig. } 5.10) \Rightarrow E_2(d_1 + d_2) = E_3(30) = 60, \\
E_3(d_1 + d_2 + d_3) = E_3(80) = 48\,\text{dB}(\mu\text{V/m}) \\
E_T R = E_1(20) - E_2(20) + E2(30) - E2(30) + E2(80) = 51\,\text{dB}(\mu\text{V/m}) \\
S_2 : (\text{Fig. } 5.10) \Rightarrow E_3(d_3) = E_3(50) = 50\,\text{dB}(\mu\text{V/m}) \\
S_2 : (\text{Fig. } 5.9) \Rightarrow E_2(d_3) = E_2(50) = 75, \\
E_2(d_2 + d_3) = E_2(60) = 73\,\text{dB}(\mu\text{V/m}) \\
S_1 : (\text{Fig. } 5.10) \Rightarrow E_1(d_3 + d_2) = E_1(60) = 60, \\
E_1(d_3 + d_2 + d_1) = E_1(80) = 48\,\text{dB}(\mu\text{V/m}) \\
E_R T = E_3(50) - E_2(50) + E2(60) - E1(60) + E1(80) = 43\,\text{dB}(\mu\text{V/m}) \\
E_R = (E_T R + E_R T)/2 = \frac{1}{2}(51 + 43)/2 = 47\,\text{dB}(\mu\text{V/m})
\end{gathered}$$

These are the results from a 1 kW transmitter; for the 100 W transmitter, we have:

$$E_a = E_R + 10\ \log \frac{P_a}{P_0} = 47 + 10\ \log \frac{100}{1000} = 37\,\text{dB}(\mu\text{V/m})$$

2. Basic loss is given by Eq. (5.36) as:

$$L_b = 137.2 - 20\log 0.5 - 47 = 96.2\,\text{dB}$$

■

5.4 Wave Propagation in MF/HF Band

The MF/HF frequency band ranges from 300 kHz to 30 MHz and is composed of two subsets, known as medium- and high-frequency bands, respectively. At lower frequencies of MF band, communications are through surface and sky waves, however, in the upper parts of MF band and in the HF band, it is mostly through sky waves using the ionosphere layer. In the previous chapter, propagation in the ionosphere was studied. In this section, we will study the methods to determine different parameters, especially electric field intensity and received power in the frequency band 2–30 MHz.

In general, calculations for the ionospheric communications in HF band are very complicated due to different parameters involved. However, this kind of communications is one of the primitive radio systems used. Medium waves (MW) and shortwaves (SW) for audio broadcasting are examples of these systems. ITU-R has prepared a recommendation for this frequency band, 2–30 MHz, that has been revised in 2005. This type of communication is simpler than other communication systems, with acceptable performance.

This method is based on the analysis of wave path for distances less than 7000 km. The composed modes include approximate equations for distances greater than 9000 km. Ionospheric characteristics and propagation parameters of the control points are used to determine the median value of MUF, field strength, and the received power of sky waves at the receiver location. In this chapter, the equations for distances less than 7000 km are presented. The reader is referred to the ITU-R P.533 recommendation for longer distances.

5.4.1 Location of the Control Points

Ionospheric communications in this band are through the great circle path between the transmitter and the receiver locations. The waves propagate using E and F2 modes for distances less than 4000 km and F2 modes for longer distances. The location of the control points are given in the following tables, based on path length and reflection layer (Tables 5.1, 5.2, and 5.3).

Table 5.1 Location of control points for basic MUF and associated electron gyrofrequency

Destination length (km)	E mode	F2 mode
$0 < D < 2000$	M	M
$2000 < D < 4000$	$T + 1000, R - 1000$	–
$2000 < D < d_{\max}$	–	M
$D > d_{\max}$	–	$T + d_0/2, R - d_0/2$

Table 5.2 Location of control points for E layer screening

Destination length (km)	F2 mode
$0 < D < 2000$	M
$2000 < D < 9000$	$T + 1000, R - 1000$

Table 5.3 Location of control points for ray path virtual reflection heights

Destination length (km)	F2 mode
$0 < D < d_{\max}$	M
$d_{\max} < D < 9000$	$T + d_0/2, M, R - d_0/2$

In these tables, all distances are in km, and the following abbreviations are used:

M: the middle point of the path
T : transmitter position
R: receiver position
$d_{\max}$: maximum length for mode F2
d_0: path length for the smallest propagating mode

5.4.2 Screening Frequency for E and F2 Layers

Considering the structure of the ionosphere layer and permanent presence of the E layer in 70–110 km altitude from the Earth, sky waves prior to entering the F layers should pass through the E layer. The frequency must be greater than a specific frequency known as E layer maximum screening frequency denoted by $f_{S/E}$, which is given by (Fig. 5.14):

$$f_{S/E} = 1.05 f_0 E \cdot \sec \varphi_i \tag{5.40}$$

$$f_{S/F} = K \cdot f_0 F \cdot \sec \varphi_i \tag{5.41}$$

$$1 < K \sec \varphi_i \leq 3.6 \tag{5.42}$$

In the above equations, φ_i is the incident angle between the waves and the ionosphere layer, which is given by:

$$\varphi_i = \arcsin\left(\frac{R_e \cos \Delta}{R_e + h_r}\right) \tag{5.43}$$

where:

R_e: Earth radius, about 6370 km
Δ: Elevation angle of the radiowaves as in Eq. (5.44)
h_r: Height of the virtual reflection point, which is equal to 110 km for E layer, and is a function of time, location, and path length for F layer.

Example 5.5. The critical frequencies in vertical radiation are 2.5 MHz and 6.3 MHz for the E and F layers, respectively; determine the frequencies for which the radiating waves will pass through these layers with an angle of 60°.

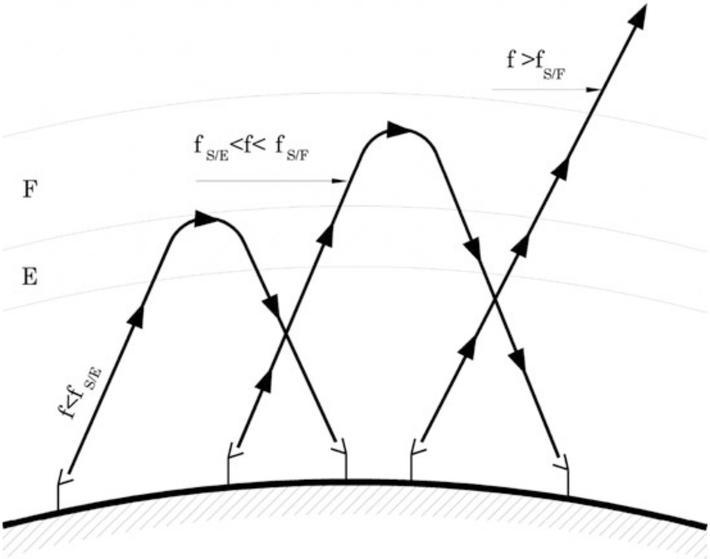

Fig. 5.14 Wave propagation in E and F layers

Solution.

$$f_{s/E} = 1.05 f_0 E \times \sec \varphi_i = 1.05 \times 2.5 \times 2 = 5.25\,\text{MHz}$$

$$f_{s/F} = K f_0 F \times \sec \varphi_i = 1.1 \times 6.3 \times 2 = 13.86\,\text{MHz}$$

■

5.4.3 Propagation Modes

There are three modes for sky waves in the E layer and for distances less than 4000 km, and six modes in F layer for distances more than 10,000 km. These modes should have all of the following properties:

E Modes:

- For distances less than 2000 km, the smallest mode or one of the two higher modes
- An elevation angle greater than 3° for reflection from the height of 110 km

F Modes:

- For Distances less than d_0, smallest mode or one of the five higher modes
- An elevation angle greater than 3°
- The frequency should be in the range: $f_{S/E} < f <$ MUF

5.4.4 Wave Elevation Angle

The wave elevation angle for all frequencies, even frequencies higher than MUF, can be determined by applying trigonometric equations. Approximate expression for it is as follows:

$$\Delta = \arctan\left(\cot\frac{d}{2R_e} - \frac{R_e}{R_e + h_r}\operatorname{cosec}\frac{d}{2R_e}\right) \tag{5.44}$$

where:

R_e: Radius of Earth, 6370 km

h_r: Height of the virtual reflection point, which is 110 km for E modes and depends on time, location, and path length for F modes.

Moreover, d is the length of one hop, which can be calculated for a path of D length with n hops as:

$$d = \frac{D}{n} \tag{5.45}$$

5.4.5 Field Intensity of Waves

For each of propagation modes, w, defined in Sect. 5.4.3, the median of the field intensity is given by:

$$E_{tw}[\text{dB}\ (\mu\text{V/m})] = 136.6 + P_t + 20\ \log f - L_t \tag{5.46}$$

where:

f: Transmitter frequency in MHz

P_t: Transmitter power in dB_{kW}

L_t: Loss of the propagation path for the corresponding mode which is given by:

$$L_t = 32.4 + 20\ \log f + 20\ \log P' - G_t + \Sigma L_j \tag{5.47}$$

P': Path length of the propagation in km for n hops, which is given by:

$$P' = 2R_e \sum_{1}^{n} [\sin(d/2R_e)/\cos(\Delta + d/2R_e)] \tag{5.48}$$

G_t: Transmitter antenna gain in dB_i

ΣL_j: The sum of additional losses, given by:

Table 5.4 Location of control points for ionospheric absorption and associated gyrofrequency

Destination length (km)	E mode	F2 mode
$0 < D < 2000$	M	M
$2000 < D < 4000$	$T+1000, M, R-1000$	–
$2000 < D < d_{\max}$	–	$T+1000, M, R-1000$
$d_{\max} < D < 9000$	–	$T+1000, T+d_0/2, M,$ $R-d_0/2, R-1000$

$$\Sigma L_j = L_i + L_m + L_g + L_h + L_Z \tag{5.49}$$

L_i: Absorption of the radiowaves for n hops which is given by:

$$L_i = \frac{n(1+0.0067R_{12})\cdot \sec\varphi_i}{(f+f_l)^2} \times \frac{1}{K}\sum_1^k AT_{\text{noon}} \cdot \frac{F(\chi_j)}{F(\chi_{j\text{noon}})} \cdot \phi_n\left(\frac{f_v}{f_0E}\right) \tag{5.50}$$

$$F(\chi) = \cos^P(0.881\chi) \tag{5.51}$$

The maximum $F(\chi)$ is equal to 0.02, and even if the equations result in a larger value, it shall be assumed 0.02.

$$f_v = f\ \cos\varphi_i \tag{5.52}$$

where:

φ_i: Angle of incident at 110 km
K: Number of control points (from Table 5.4)
f_l: The mean value of electron gyrofrequency, about the longitudinal component of the Earth's magnetic field for a height of 100 km, determined at the control points given in Table 5.4.
χ_j: Solar zenith angle at the j-th control point or 102° whichever is the smaller. The equation of time, for the middle of the month in question, is incorporated in the calculation of this parameter
$\chi_{j\text{noon}}$: Value of χ_j at local noon
AT_{noon}: Absorption factor at local noon and $R_{12} = 0$ given as a function of geographic latitude and month from Fig. 5.15.
$\phi_n(f_v/f_0E)$: Absorption layer penetration factor given as a function of the ratio of equivalent vertical-incidence wave frequency f_v to f_0E from Fig. 5.16.
P: Diurnal absorption exponent given as a function of modified dip latitude (see Recommendation ITU-R P-1239, Annex 1) and month from Fig. 5.17.

For frequencies above the basic MUF, the absorption continues to vary with frequency and is calculated assuming the same ray paths as those at the basic MUF.

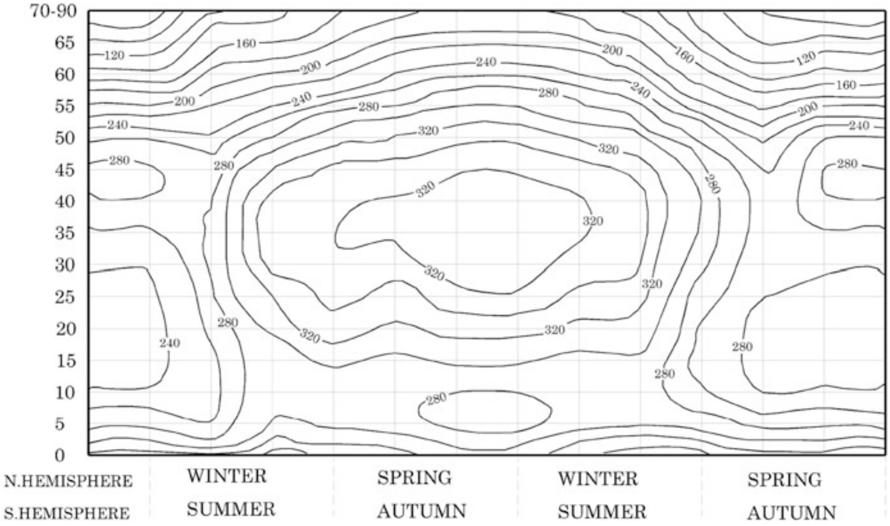

Fig. 5.15 Absorption factor, AT_{noon}

Example 5.6. If the distance between the transmitter and the receiver is 3500 km, $h_{r/E} = 110\,\text{km}$, and $h_{r/F} = 300$, find the elevation angle of the waves for communication modes, 2E, 2F2.

Solution. For 2E mode:

$$d_E = D/n \Rightarrow d_E = 1750\,\text{km}$$

$$\Delta_E = \arctan\left(\cot\frac{1750}{2\times 6370} - \frac{6370}{6370+110}\text{cosec}\frac{1750}{2\times 6370}\right)$$

$$\Delta_E = 3.15^\circ\,,\theta = \frac{1750}{2\times 6370} = 7.9^\circ\,,\ \varphi_i = 90-\theta-\Delta = 79^\circ$$

For 2F2 mode:

$$d_{2F} = \frac{D}{n} \Rightarrow d_{2F} = 1750\,\text{km}$$

$$\Delta_{2F} = \arctan\left(\cot\frac{1750}{2\times 6370} - \frac{6370}{6370+30}\text{cosec}\frac{1750}{2\times 6370}\right)$$

$$\Delta_{2F} = 14.5^\circ \quad \theta = 7.9^\circ \quad \varphi_i = 90-\theta-\Delta = 67.6^\circ$$

■

For frequencies over the base MUF, the absorption is given by:

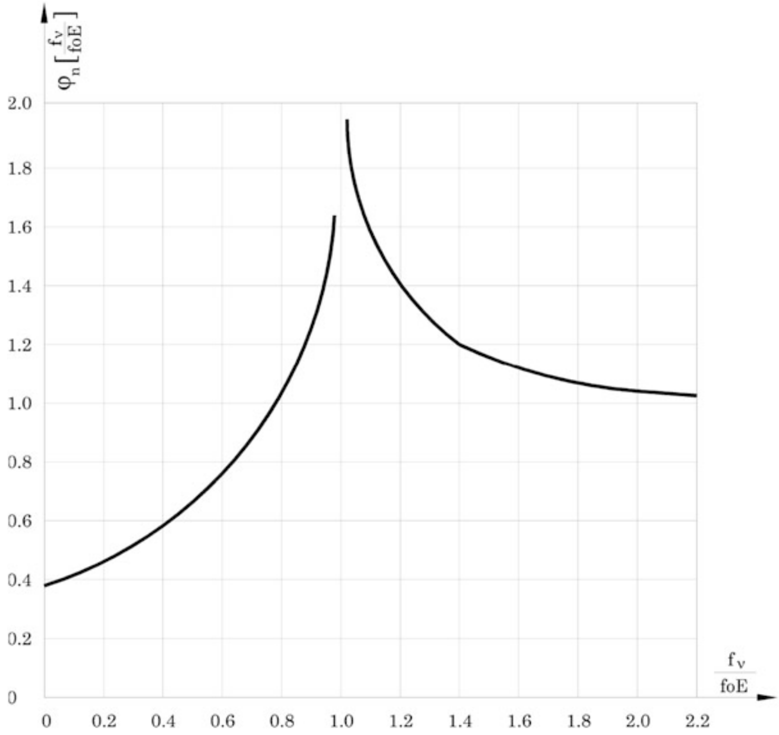

Fig. 5.16 Absorption layer penetration factor

$$L_m = 0, f < f_b(\text{MUF}) \tag{5.53}$$

$$L_m[\text{dB}] = 130[(f/f_b) - 1]^2\text{, E modes} \tag{5.54}$$

When L_m is greater than 81 dB, we assume $L_m = 81$ dB.

$$L_m[\text{dB}] = 36[(f/f_b) - 1]^{1/2}\text{,}\quad \text{F2 modes} \tag{5.55}$$

In this case, the maximum value is 62 dB.

Example 5.7. For the propagation mode of 2F2 in previous example at 10 MHz frequency, find:

1. Path length
2. Median value of electric field strength, assuming that $L_m = L_t - \text{FSL} = 30$ dB

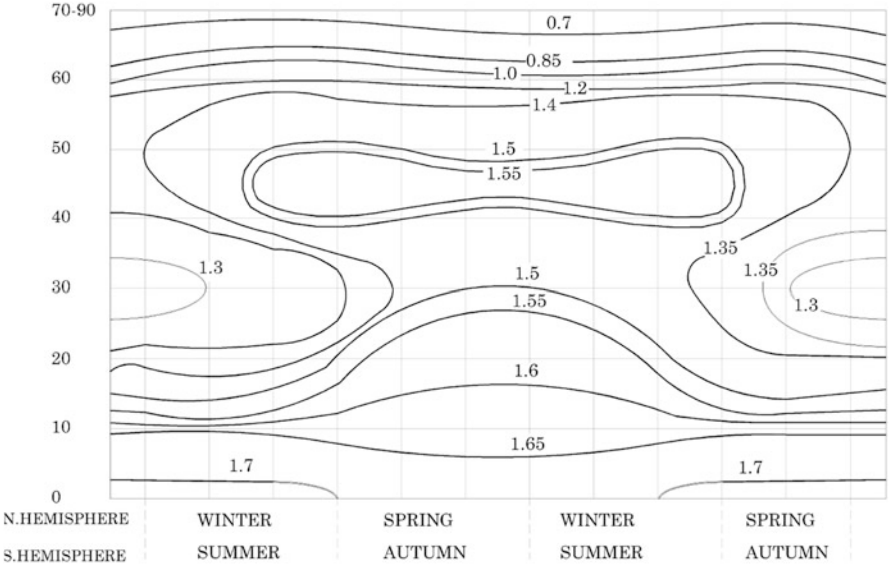

Fig. 5.17 Diurnal absorption exponent, *P*

Solution. 1.

$$\Delta = 14.5^\circ \quad d = 1750\,\text{km}$$

$$P' = 4R_e[\sin(d/2R_e)/\cos(\Delta + d/2R_e)] \quad \Rightarrow \quad P' \approx 3775\,\text{km}$$

2. Using Eq. (5.46):

$$P_t = 100\,\text{W} \quad \Rightarrow \quad P_t[\text{dB}_{\text{kW}} = 10\log 0.1 = -10]$$

$$\text{FSL} = 32.4 + 20\log f + 20\log P' = 124\,\text{dB}$$

$$E_t = 136.6 + P_t + 20\log f - \text{FSL} - L_m$$

$$E_t = -7.4\,\text{dB}(\mu\text{V/m})$$

■

5.4.6 Received Power

The received power for sky waves when the distance is less than 7000 km can be expressed by:

$$P_{rw}[\text{dB}_W] = E_{tw} + G_{rw} - 20\log f - 107.2 \tag{5.56}$$

where:

E_{tw}: Electric field strength for mode w in $\mathrm{dB}_{\mu\mathrm{V/m}}$
G_{rw}: Receiving antenna gain for mode w in dB_i
f: Radiowave frequency in MHz

For calculating total received power for all modes, we have:

$$P_r[\mathrm{dB}_w] = 10\log\sum_{W=1}^{N} 10^{(P_{rw}/10)} \tag{5.57}$$

Example 5.8. Determine the power of received signal at the receiving end, using $E_t = 20\,\mathrm{dB}(\mu\mathrm{V/m})$, antenna gain of $2\,\mathrm{dB}_i$ at $f = 15\,\mathrm{MHz}$, by assuming lossless transmission lines and connections.

Solution. Using Eq. (5.57), we have:

$$E_t = 20\,\mathrm{dB}(\mu\mathrm{V/m}),\ G_r = 2\,\mathrm{dB}_i, f = 15\,\mathrm{MHz}$$

$$P_r[\mathrm{dB}_W] = E_t + G_r - 20\log f - 107.2 = -108.7\,\mathrm{dB}_W$$

$$P_r[\mathrm{W}] = \mathrm{Antilog}(-10.87) = 1.35\times 10^{-11}\ \rightarrow\ \mathrm{P_r} = 13.5\,\mathrm{pW}$$

■

5.4.7 Signal-to-Noise Ratio

Different noises such as atmospheric, man-made, sky, and cosmic noises all are received at the receiving antenna along with the transmitted signal. For appropriate detection of the transmitted signal from noise, the signal-to-noise ratio (SNR) should be greater than a specific value. By considering F_a to be equal the sum of all noises except the thermal noise at the receiver, then:

$$S/N\,[\mathrm{dB}] = P_r - F_a - 10\log b + 204 \tag{5.58}$$

where:

P_r: Received power in dBw
F_a: External noise in dB (KTb), K is Boltzmann coefficient, and T is the reference temperature equal to 288 K
b: Channel bandwidth in Hz

Example 5.9. Considering 2.7 kHz channel bandwidth and 50 dB(KTb) for all external noises for the case specified in the example (5.8), find:

1. Received signal-to-noise ratio
2. Output signal-to-noise ratio, when the receiver noise figure is 5 dB.

Solution.

$$P_r = -108.7\,\mathrm{dB}_w, F_a = 50\,\mathrm{dB}(KTb),\; b = 2700\,\mathrm{Hz}$$

Using Eq. (5.58) results in:

$$(S/N)_i = 11\,\mathrm{dB}$$

If the amplification of the signal and the noises are the same, then:

$$(S/N)_o = (S/N)_i - N_F = 6\,\mathrm{dB}$$

■

5.4.8 Lowest Usable Frequency

The lowest usable frequency, LUF, in MF/HF band, is the lowest frequency for which the median value of appropriate SNR is obtained. The appropriate SNR is determined by the channel characteristics and quality.

5.4.9 Design Considerations

Some of the main parameters required in design of ionospheric communication systems are:

- The optimum working frequency
- Range of the communication system
- Number of hops
- Antenna elevation angle
- Transmitter power and received signal level

Note that in the design phase, some of these parameters are already determined by different practical and technical considerations and limitations.

Determination of optimum working frequency was studied in the previous chapter; the following subsections discuss some other parameters:

5.4.9.1 Number of Hops

To determine the number of hops for an ionospheric link, the maximum value of distance is required. The maximum distance is obtained if the waves are tangential to the Earth at the receiving and transmitting ends; thus, considering the curvature of the Earth yields:

$$d_{\max} = 2\sqrt{2R_e h'} \tag{5.59}$$

In this case, the antenna elevation angle is zero, and MUF has its maximum value, i.e.:

$$\mathrm{MUF} = 3.6 f_c \tag{5.60}$$

To determine f_c, the electron density $N(h')$ at the altitude h' is required. h' is the height of the related ionospheric layer which based on the experimental results are:

- F2 layer height during day time is 250–400 km
- F1 layer height during day time is 200–250 km
- F layer height during night time is 300 km
- E layer height is 110 km

So, considering the values of R_e and h', the maximum value of F layer range is:

$$3000\,\mathrm{km} < d_{\max} < 4500\,\mathrm{km} \tag{5.61}$$

With the value of $d_{\max}$, the minimum number of hops required for an ionospheric link between the two points can be calculated. Then, using geometric relations, θ is determined as follow:

$$d/2 = R_e \cdot \theta \;\rightarrow\; d = 2R_e \cdot \theta \tag{5.62}$$

5.4.9.2 Geometric Parameters

For calculating the geometric parameters of the ionospheric communication link, the following equations can be applied:

- Using Fig. 5.18 the path length of the radiowaves l yield:

$$l = \frac{2R_e \sin\theta}{\sin\varphi_i} \tag{5.63}$$

- Using Fig. 5.18 to determine the antenna elevation angle, Δ, the angle between the propagation direction and the tangent line to the Earth at point T or R, yields:

$$\Delta = 90 - \theta - \varphi_i \tag{5.64}$$

To cover a specific range, first θ is calculated from:

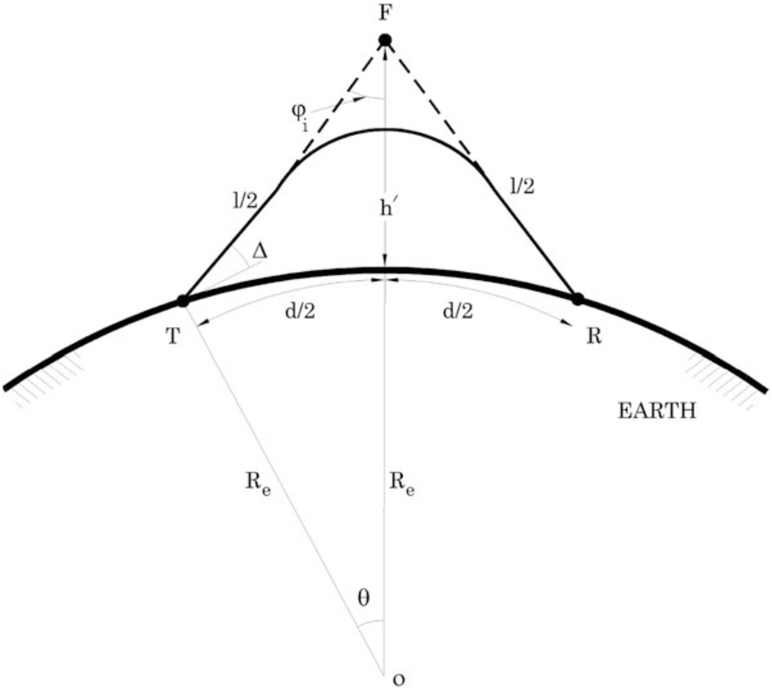

Fig. 5.18 Geometric parameters of ionospheric link

$$\theta(\text{rad}) = \frac{d}{2R_e} \tag{5.65}$$

and then φ_i and Δ are determined.

5.4.9.3 Transmitter Power and Received Signal Level

In general, the received signal power is expressed by the following formula:

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{(4\pi l/\lambda)^2} \cdot L_a \cdot L_m \tag{5.66}$$

where:

P_r:	Received signal power in watt
P_t:	Transmitter radiated power in watt
G_t, G_r:	Transmitter and receiver antenna gains
l:	Path length in meter
λ:	Carrier wavelength in meter
L_a:	Energy absorption coefficient in wave path

L_m: Coefficient for polarization losses due to Faraday rotation, reflection in multi hop paths, and gain of wave concentration because of the curvature of ionosphere is given by:

$$L_m = (L_p \times L_r)/G_i \tag{5.67}$$

In logarithmic system, this equation can be written as:

$$P_r[\mathrm{dB}_W] = P_t[\mathrm{dB}_W] + G_t[\mathrm{dB}_i] + G_r[\mathrm{dB}_i] - \mathrm{FSL}[\mathrm{dB}] - L_m[\mathrm{dB}] - L_a[\mathrm{dB}] \tag{5.68}$$

in which FSL is the free-space loss, given by:

$$\mathrm{FSL} = 32.4 + 20\log f[\mathrm{MHz}] + 20\log l[\mathrm{km}] \tag{5.69}$$

Example 5.10. The distance between two points is 6000 km, find:

1. Minimum number of hops required for ionospheric communication
2. Elevation angle of the transmitting and the receiving antennas for equal hops and angle of $\varphi_i = 72°$
3. Height, h'
4. Maximum working frequency

Solution. 1. Considering that in ionospheric communication the maximum path length for one hop is 4500 km for reflection from F2 layer and 3900 km for reflection from layer F, the mentioned link needs at least two hops, each with a length of 3000 km.

2.

$$\theta = \frac{d}{2R_e} = \frac{3000}{2 \times 6370} = 0.235\,\mathrm{rad} \quad \Rightarrow \quad \theta = 13.5°$$

$$\Delta = 90 - \theta - \varphi_i = 4.5°$$

3. For h', considering TOF triangle in Fig. 5.18:

$$\frac{R_e}{\sin\varphi_i} = \frac{R_e + h'}{\sin(90 + \Delta)} = \frac{R_e + h'}{\sin(\theta + \varphi_i)} \quad \Rightarrow \quad h' = 307\,\mathrm{km}$$

4. For $h' = 307$ km, using the diagram of electron density given in the previous chapter, the electron density is 5×10^{11} el/m^3; thus:

$$f_c = 9\sqrt{N} = 6.3\,\mathrm{MHz}$$

$$\mathrm{MUF} = f_c \times \sec\varphi_i = 20.4\,\mathrm{MHz}$$

■

5.4.10 *Wave Propagation in MF Band*

MF band includes frequency spectrum from 300 kHz to 3 MHz. This band is used for a number of applications which among them maritime and sound broadcasting are more important.

5.4.10.1 Propagation Modes

As shown in Fig. 5.19, radiocommunication in MF band at frequencies below 2 MHz is based on D, E, and F propagation modes. In ground wave propagation of MF band, the parameters of the land in propagation path are important. The amplitude of the waves depends on the electric characteristics of the path between the transmitter and receiver and does not change with atmospheric conditions. In this case, distance limitation is due to lightning and man-made noise.

During the day time, sky waves are strongly attenuated by the lower parts of the D layer; thus, this layer almost blocks the sky wave propagation in day time; during night time, sky waves in the ionosphere play a more important role. The E and F modes can improve the communication range. On the other hand, different receiving waves at the receiver end can cause considerable impairment in the receiver. Receiving radio waves from other sources of this frequency band may cause additive interference. Because of the internal and external interferences, MF band communication, specially broadcasting, is mostly based on the ground wave propagation.

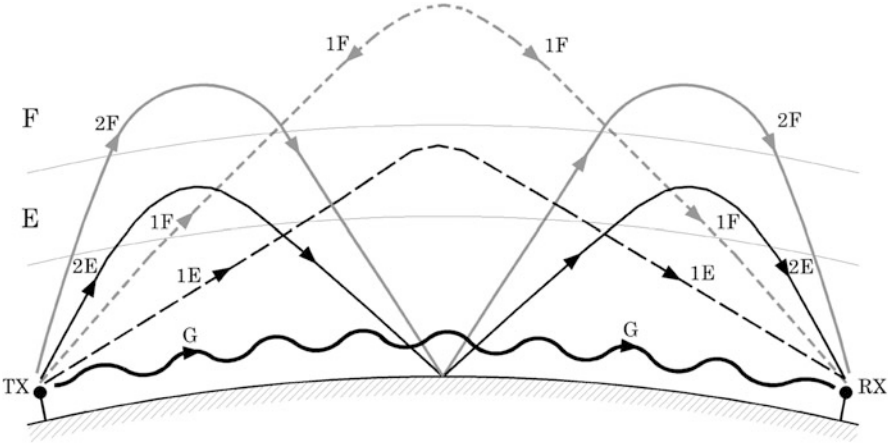

Fig. 5.19 Propagation modes of lower MF band

5.4.10.2 Time Delay in Multipath Routes

As mentioned before, in MF band communications, radiowaves (without considering external interference) arrive at the receiver, through the following paths:

- Ground waves
- E layer propagation modes
- F layer propagation modes

The electric field strength received through each of these paths are different from others, and its amplitude depends on the distance, terrain structure of the path, radio frequency, day time, and date of the year. Moreover, time delay between these waves can reach up to a few milliseconds. More details on this phenomenon are given in Figs. 4.10, 4.11, 4.12, and 4.13 of the previous chapter.

5.4.10.3 Fluctuations of the Received Signal Amplitude

The ground waves in MF band can be assumed almost with no fading effect; however, the sky waves in this band under the effect of day time are subject to its median fluctuation in the range of 3.5–9 dB. Moreover, experiments reveal that the Doppler effect, caused by movements of the ionosphere layers, has almost no effect on MF band communications.

Although, separating the receied waves to ground and sky components is not possible at the receiver, a mixed wave with amplitude e is received relating to the amplitude of ground (e_e) and sky (e_i) components by:

$$e = \sqrt{e_e^2 + e_i^2} \tag{5.70}$$

Example 5.11. The parameters of an ionospheric communication link, in 1F2 propagation mode and with a distance of 2500 km between the transmitter and the receiver, are given as:

- Transmitter output power: 500 kW
- Radio frequency: 15 MHz
- Antenna gain: 3 dB$_i$ at $\Delta = 6°$
- Other losses: 42 dB

Determine the propagated wave power at the receiving end.

Solution.

$$\theta = \frac{d}{2R_e} \quad \Rightarrow \quad \theta = \frac{2500}{2 \times 6370} = 0.196\,\text{rad} = 11.2°$$

$$\varphi_i = 90 - \Delta - \theta \quad \Rightarrow \quad \varphi_i = 72.8°$$

$$l = \frac{2R_e \sin\theta}{\sin\varphi_i}$$

Free-space loss is:

$$\text{FSL} = 32.4 + 20\log 15 + 20\log 2590 = 124.2\,\text{dB}$$

Using Eq. (5.67), we have:

$$P_r = 57 + 6 - 124.2 - 42 = -103.2\,\text{dB}_W$$

$$P_r[\text{W}] = \text{Antilog}(-10.32) = 4.79 \times 10^{11} \quad \Rightarrow \quad P_r = 47.9\,\text{pW}$$

■

5.5 Summary

Summary of main issues provided in the present chapter includes:

- Application of radio systems in MF/HF frequency band was listed and their progress trend was expressed.
- Major aspects of MF/HF radio systems were specified.
- Medium properties for MF/HF frequency bands were explained and some useful graphs were presented.
- Limitations of radiowave propagation inside seawater and its design considerations were explained.
- Surface waves, including affecting factors such as $\epsilon_r, \mu_r, \sigma$, and δ, were presented.
- Empirical formulas and applied procedures to calculate received signal level for surface waves considering vertically and horizontally polarized waves were introduced.
- ITU-R-based curves for ground wave propagation were presented.
- Calculation procedure for received field strength of a mixed path was introduced.
- MF/HF propagation effects and its main components such as control points and ionospheric absorption were described.
- Gyrofrequency, wave elevation angle, and screening frequency associated with MF/HF wave propagation were introduced.
- Expressions to calculate field strength and received signal power were given and all related factors were explained.
- Signal-to-noise ratio defined and its impact on received signal were indicated.
- Suitable modes of propagation, number of hops, and geometric parameters were specified.
- Modes of propagation for lower HF band, time delay in multipath reception, and received signal level fluctuation were introduced.

5.6 Exercises

Questions

1. Name the major propagation modes in 3 kHz to 30 MHz band.
2. Explain the applications of each VLF, LF, MF, and HF bands. It can be done by either ITU frequency band classification or catalogs of radio equipments in these bands.
3. Determine different types of antennas used at frequencies below 30 MHz, with details of polarization, gain, and approximate dimension.
4. List the reasons of non-efficient operation of radiocommunications under seas and oceans, considering the diagram for penetration depth of waves by operating frequency.
5. Considering Fig. 5.2, calculate the loss of radio waves at frequencies 25, 50, and 75 kHz at a distance of 20 m.
6. What are the main parameters of underwater communications systems?
7. What is the coupling attenuation of waves in communication with submarines and land bases, and how does it depend on frequency?
8. What is the difference between ground and surface waves? With increasing the antenna height, which component would decrease more?
9. Explain the effects of moisture and temperature on the electric characteristics of the Earth.
10. Define the parameters p and b in surface waves, and explain their equations for vertical and horizontal polarizations.
11. What is the ground flatness criteria for surface waves and on what parameters does it depend? What is its range in 10 kHz to 30 MHz band?
12. What polarization has a greater rate of attenuation on surface waves?
13. In the ITU-R graphs for ground waves, what components are defined as parameters and what components are defined as their results?
14. What are the conditions in using the ITU-R graphs for ground waves?
15. Define and give equations for the screening frequency of radio waves from E and F layers.
16. What are the common propagation modes for distances less than 4000 km and distances between 4000 and 10,000 km?
17. Give an equation for the received field strength in terms of transmitter output power. Define all parameters and their units.
18. What are the wave attenuation components in ionospheric propagation? Give the equation for each component.
19. Define the elevation angle of radio waves and give its equation.
20. Give the equation for the received power in terms of transmitter output power, distance, and frequency, and determine all parameters and their units.
21. Define the signal-to-noise ratio, and give its appropriate values in urban and rural locations
22. Explain the maximum and minimum usable frequency in ionospheric radiocommunications.

23. What are the major design considerations in MF/HF frequency band radio systems?
24. Give the equations for geometrical parameters of ionospheric links and their units.
25. Explain the effects of D layer in ionospheric communications and propagation modes in MF band.
26. Explain time delay and amplitude fluctuations in received signal level at the first half of MF band.

Problems

1. Calculate the penetration depth of seawater at frequencies 10 kHz, 100 kHz, and 1 MHz when temperature is 27 °C and 10 °C, respectively.

2. In a communication link between an onshore station and a submarine vessel located at 10 m below sea level working at frequency $f = 20\,\text{kHz}$, find the attenuation of seawater if neglecting the free-space loss and assuming 64 dB coupling loss.

3. Using Figs. 5.5 and 5.6 in MF, HF, and UHF bands, determine the variations of ϵ_r, μ_r, and σ of the following media:

(a) Wet Earth (c) Dry Earth
(b) Seawater (d) Pure water at 20 °C

4. Determine the variations of ϵ_r, σ, and δ at the frequencies between 10 kHz and 100 MHz by using curves presented in this chapter.

5. A vertical antenna radiates 20 MHz surface radiowaves. The electrical characteristics of the Earth are $\epsilon_r = 15$ and $\sigma = 0.001\,\text{S/m}$:

(a) Determine the type of propagating wave.
(b) Determine the maximum distance to use the flatness condition of the Earth.
(c) Calculate the attenuation at the distance of 20 km.
(d) Calculate the attenuation at the distance of 40 km and compare it with the result of (c).

6. Using figures of the text, calculate the electric field intensity of propagating ground wave over seawater with $\epsilon_r = 70$ and $\sigma = 5\,\text{S/m}$ in the following conditions:

(a) TX power of 1 kW radiating on 10 kHz at the distances of 100 and 200 km.
(b) TX power of 1 kW radiating on 20 MHz at the distances of 100 and 2000 km.
(c) Repeat parts (a) and (b) if the transmitter power increases to 2 kW.

7. Using figures of the text, calculate the attenuation of surface waves of 10 MHz along a 20 km path length. The electrical characteristics of the Earth are $\epsilon_r = 12$ and $\sigma = 0.005\,\text{S/m}$.

8. Using the graphs of ITU-R recommendation P. 368 for ground waves with the specified conditions for antenna height, calculate the electric field strength in dB

(μV/m) and received power at the frequency of 300 kHz at a distance of 200 km from the transmitting point when:

(a) Radiation power of 5 kW, $\epsilon_r = 22$, and $\sigma = 0.003\,\text{S/m}$.
(b) Radiation power of 1 kW, $\epsilon_r = 3$, and $\sigma = 0.0001\,\text{S/m}$.

9. A 100 W transmitting antenna at the frequency of 15 MHz is vertically placed near the Earth surface. Assuming transmitter and receiver antennas of unity gain, 20 km path length, $\epsilon_r = 10$, and $\sigma = 0.004$ S/m, calculate the received signal level.

10. In Problem 8, change the frequency to 3 MHz and calculate:

(a) Appropriate antenna height
(b) Received power at a distance of 100 km from a transmitter with 2 kW radiation power.

11. A 500 W transmitting antenna at the frequency of 8 MHz is vertically placed near the Earth surface. Assuming transmitter and receiver antennas of unity gain, 30 km path length, $\epsilon_r = 12$, and $\sigma = 0.004$ S/m, calculate the received signal power.

12. Assuming the critical frequency of f_0E and f_0F to be 3 MHz and 6 MHz, respectively:

(a) Calculate the screening frequencies of the waves for E and F layers at 45° incident angle.
(b) Determine the appropriate propagating mode at distances of 1000 and 3000 km when 8 and 3.6 MHz radiowaves are used during day time and night time, respectively.

13. Determine appropriate elevation and azimuth angles of an ionospheric radiowave to be detected properly at distances between 1800 and 2200 km when using either E layer of 110 km height or F layer of 300 km height during day time and night time, respectively.

14. A 3000 km communication link uses 1F2 mode with the ionospheric layer height of $h_r = 300$ km, calculate:

(a) Elevation and azimuth angles of the transmitter antenna.
(b) Radiowave path length.

15. In previous problem, when $f = 12$ MHz and transmitter radiation power is equal to 10 kW, calculate:

(a) Free-space loss
(b) Electric field strength at the receiver, assuming other losses is equal to 32 dB.

16. Repeat Example 5.8 for 2E mode and $f = 4$ MHz.

17. The electric field strength at the receiver with a 3 dB$_i$ antenna and 8 MHz frequency is 25 dB (μV/m). Neglecting the feeder and connection losses, calculate the receiver input power.

18. The equivalent environment temperature is equal to 300 K resulting in 50 dB external noise and the radio channel bandwidth is 3 kHz. Calculate:

(a) Signal-to-noise ratio at the receiver input when the equivalent received power is $P_r = -105\,\text{dBw}$.
(b) Signal-to-noise ratio at the receiver output when the receiver noise figure is 6 dB.

19. A transmitter using 5 dB_i antenna gain is to cover the area at an average distance of 5000 km. The required electric field strength is 2 $\mu\text{V/m}$; the receiver antennas are of unity gain. Determine:

(a) Minimum number of radio hops to make connection.
(b) Transmitter antenna elevation angle when $\varphi_i = 71^\circ$
(c) Virtual height, h'
(d) Working frequency

20. A ionospheric link have the following characteristics:

- Transmitter power: 5 kW
- path length: 2000 km
- Working frequency: 12 MHz
- Radiation angle: 72°
- Antenna gain: 5 dB_i
- $L_m = 8\,\text{dB}$ and $L_a = 28\,\text{dB}$

(a) Calculate free-space loss.
(b) Determine the received power
(c) Suggest solutions to increase the received power.

21. Calculate the received power and actual length of the radiowave trajectory in an ionospheric link with the following characteristics:

- Transmitter power: 1 kW
- path length: 2500 km
- Working frequency: 10 MHz
- Radiation angle: 72°
- Antenna gain: 10 dB_i
- $L_m = 9.5\,\text{dB}$ and $L_a = 30\,\text{dB}$

22. The characteristics of an ionosphere link working in 1F2 mode between a transmitter and receiver with a distance of 3000 km is as follows:

- Transmitter power: 500 kW
- Working frequency: 15 MHz
- Antenna gain: 3 dB_i at $\Delta = 6^\circ$
- Other losses: 32 dB

Calculate the electric field strength and the received power.

Chapter 6
Terrestrial Mobile Radio Propagation

6.1 Introduction

The basic principles regarding radiowave propagation in the mobile radio systems and effects of different phenomena and parameters on these waves are outlined in this chapter. The issues provided are helpful in design and application of this kind of radiowaves. Frequency bands from LF up to UHF and even a certain part of SHF band are used in several types of mobile radio systems such as land, maritime, aeronautical, and satellite networks.

Because of some special characteristics, LF and VLF bands are mostly used in submarine communications, which were considered in Chap. 5. Using this frequency band, due to the electrical characteristics of sea water, more attenuation at higher bands is unavoidable.

MF and HF bands are mostly used in maritime and aeronautical communications and also in radio broadcasting systems. Ground waves or ionospheric waves, by using D, E, and F layers, could be transmitted over several hundreds or even thousands of kilometers by using suitable frequency and appropriate transmitter and receiver antennas.

Application of these bands due to the following points is limited:

- Passing through ionospheric layers
- Suffering atmospheric adverse effects on radiowaves
- Suffering galaxy and ground noises
- Limited bandwidth and channel capacity

At the present time, the VHF and UHF bands are the most interesting and widely used in different kinds of land mobile radio-communication services. As shown in Fig. 6.1, these bands can be employed in the following main applications:

- Satellite communications
- Line-of-sight radio-communications

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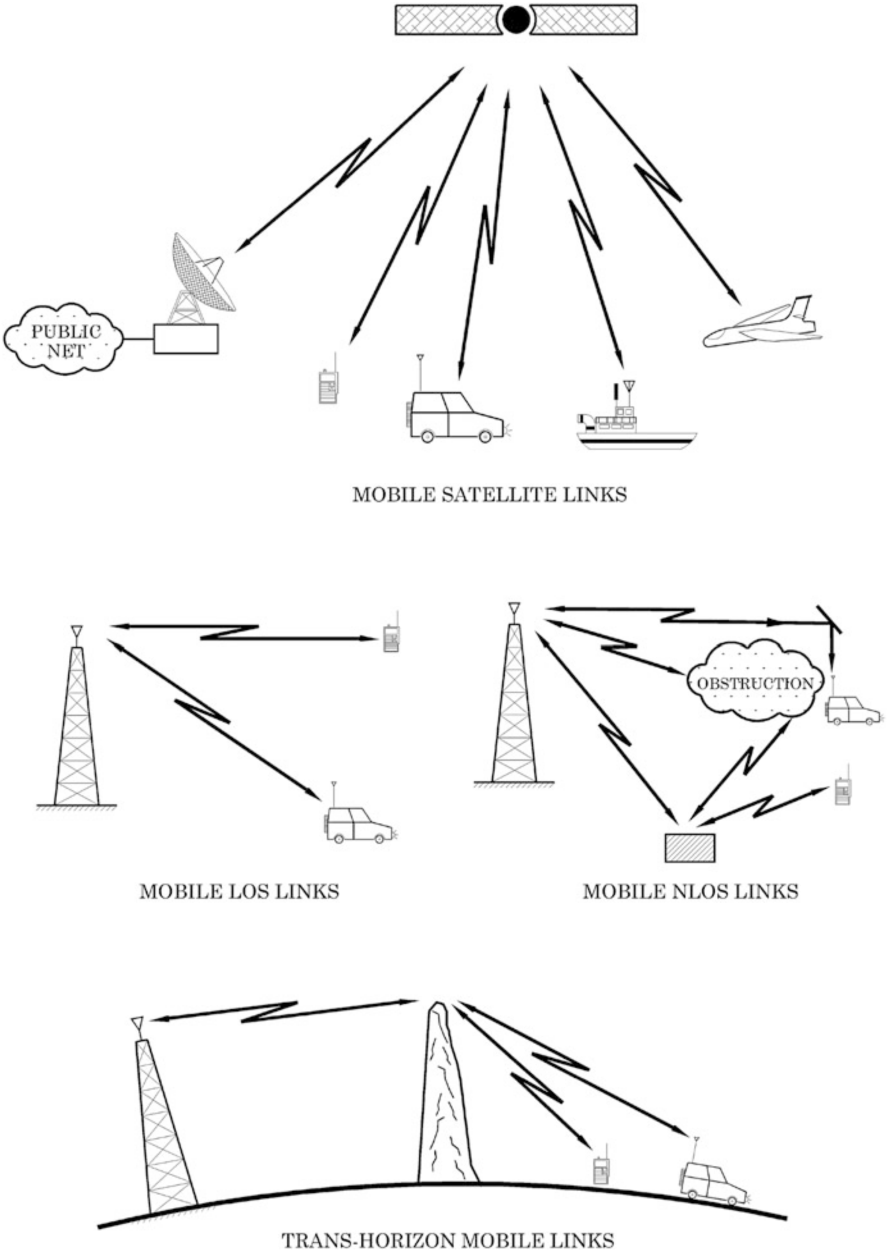


Fig. 6.1 Main types of terrestrial mobile radio systems

- Non-line-of-sight radio-communications
- Over horizon radio-communications

Mobile radio-communications in VHF and UHF bands in terms of tropospheric waves are considered in this section. Phenomena such as diffraction, reflection, scattering, and attenuation are effective mechanisms to characterize such propagation environments.

6.2 Diffraction Loss

6.2.1 Fresnel Zones

Diffraction occurs when the radiowaves face the Earth or other obstacles. For its calculations, effects of the atmospheric refraction in the transmission path shall be taken into account by evaluating the geometric parameters such as diffraction angle, height, and distance from the obstacle. In the next sections, calculation procedure for diffraction loss of different obstacle types and finally the appropriate algorithm will be given for calculation using transmission path profile.

In the first step for calculating the diffraction loss, it is necessary to determine how much of the first Fresnel zone for different quantities of the Earth radius (different values of K-factor) is occupied by the obstruction. For each point with path distance L, the first Fresnel radius is calculated from the following equation:

$$r_1 = \sqrt{\frac{L_1 \cdot L_2}{L} \times \lambda} \tag{6.1}$$

In the above equation, L_1 and L_2 are distances between the considering point and two ends of the radio path and λ is wavelength, all in same units.

Assuming the natural spherical Earth bulge, if every point of the terrain is lower than the wave path equal to 100 % of the first Fresnel radius at $\mathrm{K} = 1.33$ in that point or if every point of the terrain is lower than the wave path equal to 60 % of the first Fresnel radius in that point, then the radio path is assumed to be in the line-of-sight (LOS) condition, and no diffraction is experienced. Otherwise, for link budget calculation, the diffraction loss shall be taken into account.

Basically, for microwave or point-to-point link design, the LOS condition shall be obtained, while in the mobile radio networks, in addition to the LOS paths, non-line-of-sight (NLOS) conditions based on diffraction phenomenon shall be considered as well.

Example 6.1. A mobile communications system is working at 400 MHz. In the case that the communication path-length is equal to 30 km and $K = 1.33$:

1. Calculate the maximum first Fresnel radius for this path.
2. For the flat Earth, what is the maximum of Earth bulge and where is it located?

3. For LOS communications, what is the distance between the mid-path and the TX-RX connecting line?

Solution. 1.

$$\lambda = C/f = 0.75\,\text{m}$$

Considering this mathematics theorem which mentions that if the sum of two variables is constant, the multiplication of them is maximum when they are equal to each other ($L_1 = L_2 = L/2$), the maximum of the first Fresnel radius will occur in the mid-path and its value is equal to

$$r_1 = \sqrt{\frac{L_1 \cdot L_2}{L}\lambda} = \sqrt{\frac{15 \times 15}{30} \times 10^3 \times 0.75} = 75\,\text{m}$$

2. According to the above fact, the Earth bulge will be maximum in the mid-path:

$$h_0 = \frac{500 d_1 d_2}{KR_e} \quad \Rightarrow \quad h_0 = 13.25\,\text{m}$$

3. For LOS communications, the mid-path point distance should be at least $h_0 + r_1 = 88.25\,\text{m}$, lower than the TX-RX connecting line. ■

6.2.2 Basic Concepts

Although diffraction is produced only by the surface of the ground or other obstacles, the mean atmosphere refraction shall be taken into account on the transmission path to evaluate the geometrical parameters situated in the vertical plane of the path (angle of diffraction, radius of curvature, height of obstacle). For this purpose, the path profile has to be traced with the appropriate equivalent Earth radius which may be assumed 8500 km for standard conditions.

Diffraction of radiowaves over the Earth surface is affected by terrain irregularities. In this context, before going further into the prediction procedures for this propagation mechanism, a few basic concepts are given in this section based on ITU-R recommendations.

6.2.2.1 Penumbra Width

The transition from light zone to shadow zone when the path of radiowaves is obstructed defines the penumbra region. This transition takes place along a narrow strip (penumbra width) in the boundary of geometric shadow.

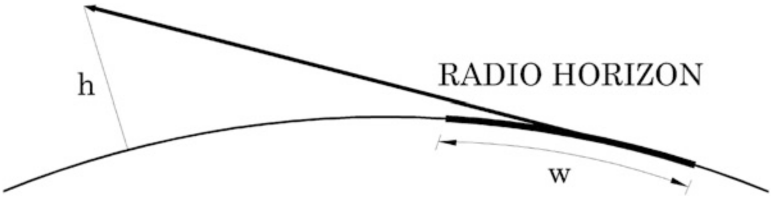


Fig. 6.2 Penumbra width

Figure 6.2 shows the penumbra width (W) in the case of a transmitter located at a height, h, above a smooth spherical Earth, which is given by

$$W = \left[\frac{\lambda \alpha_e^2}{\pi}\right]^{1/3} \tag{6.2}$$

where:

λ: Wavelength (m)
R'_e: Effective Earth radius (m)

6.2.2.2 Diffraction Zone

The diffraction zone of a transmitter extends from the LOS distance where the path clearance criterion is satisfied (equal to 60–100 % first Fresnel zone radius, R_1), up to a distance well beyond the transmitter horizon where the mechanism of troposcatter becomes predominant.

6.2.2.3 Obstacle Surface Smoothness Criterion

If the surface of the obstacle has irregularities not exceeding Δh,

$$\Delta h = 0.04\left[R\lambda^2\right]^{1/3} \text{ m} \tag{6.3}$$

where:

R: Obstacle curvature radius (m)
λ: Wavelength (m)

Then the obstacle may be considered smooth and the relevant methods may be used to calculate the attenuation.

6.2.2.4 Isolated Obstacle

An obstacle can be considered isolated if there is no interaction between the obstacle itself and the surrounding terrain. In other words, the path attenuation is only due to the obstacle alone without any contribution from the remaining terrain. The following conditions must be satisfied for isolated obstacles:

- No overlapping between penumbra widths associated with each terminal and the obstacle top
- The path clearance on both sides of the obstacles be, at least, 0.6 of the first Fresnel zone radius
- No specular reflection on both sides of the obstacle

6.2.2.5 Types of Terrain

Depending on the numerical value of the parameter Δh used to define the degree of terrain irregularities, three types of terrain can be classified:

- **Smooth Terrain**
  The surface of the Earth can be considered smooth if terrain irregularities are of the order or less than 0.1 r_1, where r_1 is the maximum value of the first Fresnel zone radius in the propagation path. In this case, the prediction model is based on the diffraction over the spherical Earth.
- **Isolated Obstacles**
  The terrain profile of the propagation path consists of one or more isolated obstacles. In this case, depending on the idealization used to characterize the obstacles encountered in the propagation path, the prediction models for diffraction should be used.
- **Rolling Terrain**
  The profile consists of several small hills, none of which form a dominant obstruction. Within its frequency range Rec., ITU-R, P.1546 is suitable for predicting field strength but it is not a diffraction method.

6.2.3 Diffraction of Spherical Earth

Radiowaves facing the Earth surface are affected because of diffraction mechanism. The following conditions should be considered in using equations related to diffraction:

- This calculation method is applicable to over-horizon paths.
- The results are reliable for the shadow zone.
- The attenuation in shadow zone will be changed with troposcatter mechanism.

Diffraction calculations are very complicated and it is necessary to study competent references to obtain its exact and complete approaches and equations. In this section, some simplified and practical equations which are needed for engineering and design application are presented. These equations are mostly based on the ITU-R recommendations and reports. Earth electrical characteristic relevant to loss of diffraction are introduced by parameters K_V and K_H. These parameters are normalized Earth admittance and defined for horizontal and vertical polarizations with K_V and K_H notations, respectively:

$$K_H = \left(\frac{\lambda}{2\pi R'_e}\right)^{1/3} \cdot \left[(\epsilon - 1)^2 + (60\lambda\sigma)^2\right]^{-1/4} \tag{6.4}$$

$$K_V = K_H \cdot \left[\epsilon^2 + (60\lambda\sigma)^2\right]^{1/2} \tag{6.5}$$

In the above equations:

R'_e: Effective Earth radius in meter
ϵ: Earth effective relative permittivity
σ: Earth effective conductivity in (s/m)
λ: Wavelength in meter

Parameter K_V and K_H values are shown in Fig. 6.3.

In practical applications for small values of K ($K < 0.001$), the Earth electrical characteristic effects can be ignored, while for large values of K ($K > 0.001$), the following formula shall be used for calculating the ratio of diffraction field intensity (E) over free-space field intensity (E_0):

$$20\log\frac{E}{E_0} = F(X) + G(Y_1) + G(Y_2)\,\text{dB} \tag{6.6}$$

In the above formula, X is the normalized length of the path between the transmitter and receiver antennas, at the normalized heights Y_1 and Y_2:

$$X = \beta\left[\frac{\pi}{\lambda {R'_e}^2}\right]^{1/3} \cdot d \tag{6.7}$$

$$Y = 2\beta\left[\frac{\pi^2}{\lambda^2 R'_e}\right]^{1/3} \cdot h \tag{6.8}$$

For practical application, the above equation can be expressed as follows:

$$X = 2.2\beta f^{1/3} {R'_e}^{-2/3} d \tag{6.9}$$

$$Y = 9.6 \times 10^{-3} \beta f^{2/3} {R'_e}^{-1/3} h \tag{6.10}$$

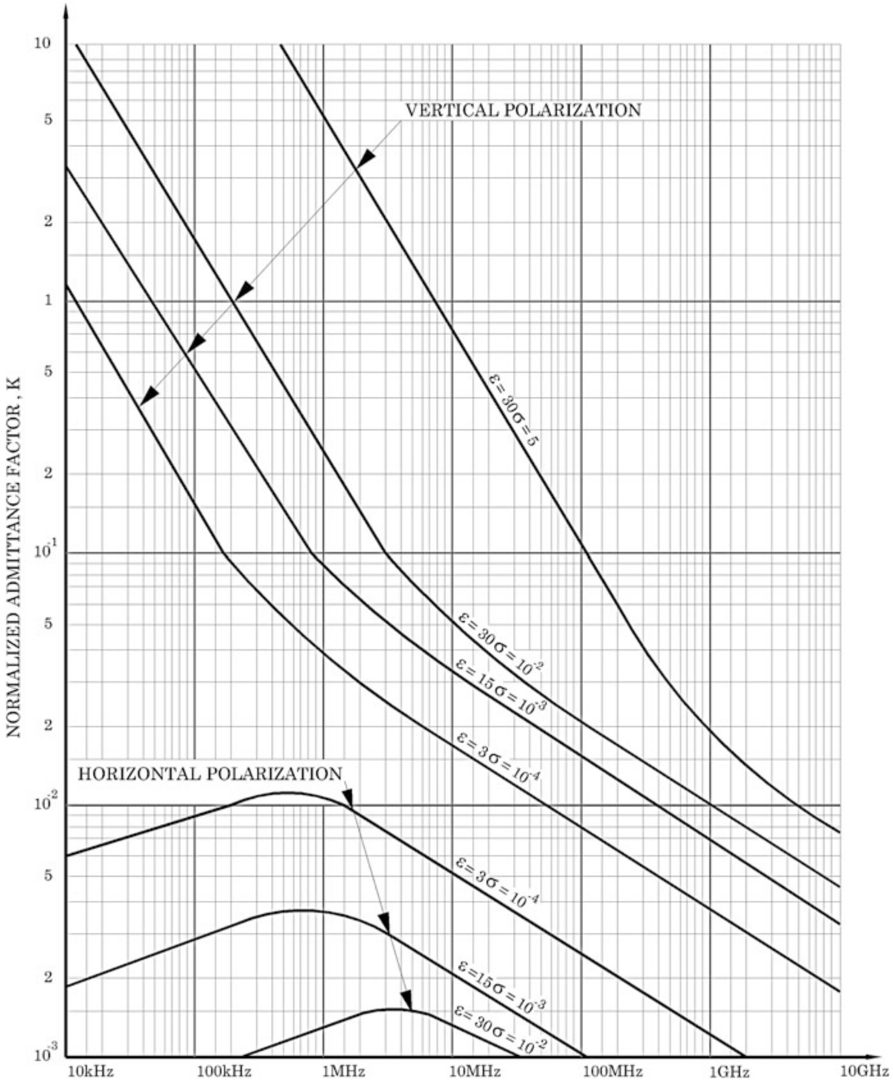


Fig. 6.3 Earth normalized admittance vs. frequency (Ref.: ITU-R, P-526)

where:

d: Path distance in km
R'_e: Effective Earth radius in km
h: Antenna height in meter
f: Frequency in terms of MHz

Considering the Earth type, for different kinds of polarization, the parameter β is defined as follows:

$$\beta = \frac{1 + 1.6K^2 + 0.75K^4}{1 + 4.5K^2 + 1.35K^4} \tag{6.11}$$

For horizontal polarization at all frequencies and for vertical polarization above 20 MHz over land or 300 MHz over sea, β is 1.

Other parameters in Eq. (6.6) can be expressed as follows:

$$F(X) = 11 + 10\log(X) - 17.6X \tag{6.12}$$

$$G(Y) = 17.6(1.1 - Y)^{1/2} - 5\log(Y - 1.1) - 8, \quad Y > 2 \tag{6.13}$$

$$G(Y) = 20\log(Y + 0.1Y^3), \quad 10K < Y < 2 \tag{6.14}$$

$$\begin{aligned} G(Y) &= 2 + 20\log K + 9\ \log(Y/K) \\ &\cdot[\log(Y/K) + 1], \ \ K/10 < Y < 10K \end{aligned} \tag{6.15}$$

$$G(Y) = 2 + 20\log K, \quad Y < K/10 \tag{6.16}$$

Example 6.2. In a mobile radio-communications network in 400 MHz band, assuming 50 km path length and $K = 1.33$:

1. Calculate the normalized admittance for horizontal and vertical polarized waves ($\epsilon_r = 3$ and $\sigma = 10^{-4}$).
2. Calculate the normalized distance and its loss.

Solution. 1. The following result is obtained using Fig. 6.2:

$$K_H = 1.6 \times 10^{-3}, \quad K_V = 5 \times 10^{-3}$$

2.

$$\beta = 1, \quad R'_e = 8500, \quad d = 50, \quad f = 400$$

$$X = 2.2 \cdot \beta f^{1/3} \cdot {R'_e}^{-2/3} \cdot d \quad \Rightarrow \quad X = 1.946$$

According to Eq. (6.12), distance attenuation value $F(X)$ is

$$\begin{aligned} F(X) &= 11 + 10\ \log 1.946 - 17.6 \times 1.946 \\ &= -20.36\,\text{dB} \end{aligned}$$

■

6.2.4 Obstacle Diffraction

Most of propagation paths in point-to-area networks including mobile radiocommunications have one or more separate obstacles, so estimating these obstacle losses is useful. For this purpose, an ideal shape and exact geometry for these obstacles should be considered. In practice, the path obstacles are combination of these shapes, so the presented method is an acceptable approximation for calculating the total loss.

Equations provided in this section are applicable for wavelengths which are smaller than obstacle dimensions; generally, they can be used for frequencies greater than 30 MHz. The different basic types of obstructions are listed as follows:

- Single knife-edge obstacles
- Single rounded obstacles
- Double isolated obstacles
- Multiple isolated obstacles

6.2.5 Single Knife-Edge Obstacles

Different parameters and knife-edge obstacle situations in radiowave propagation are shown in Fig. 6.4. All geometrical parameters could be expressed by diffraction parameter denoted by ϑ. The required relations for diffraction estimation are

$$\vartheta = h \times \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} \tag{6.17}$$

$$\vartheta = \theta \times \sqrt{\frac{2}{\lambda\left(\frac{1}{d_1} + \frac{1}{d_2}\right)}} \tag{6.18}$$

$$\vartheta = \sqrt{\frac{2h\theta}{\lambda}} \tag{6.19}$$

$$\vartheta = \sqrt{\frac{2d}{\lambda}\alpha_1\alpha_2} \tag{6.20}$$

In the above equations, the parameters are defined as follows:

h: Distance between the obstacle peak and the straight line connecting the path ends to each other. The value of h is in meter, and if it was under the path line, it has a negative sign.

d_1, d_2: Distances between the two path ends and the obstacle peak in terms of meter.

d: Path length between the transmitter and the receiver in terms of meter.

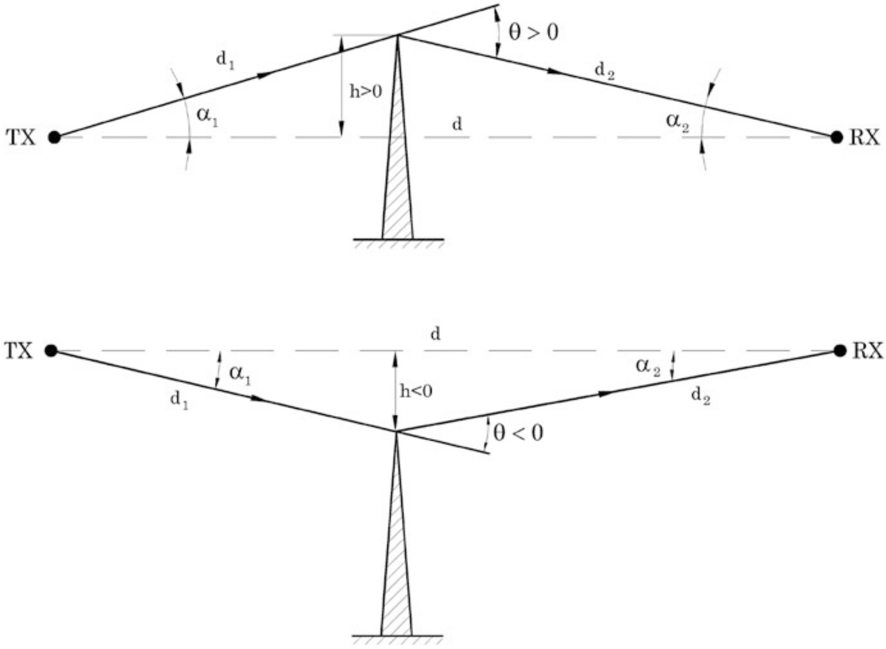


Fig. 6.4 Geometrical parameter of knife edge obstacle

θ: Diffraction angle in radian with same sign as h.
$\alpha_1,\ \alpha_2$: Angles between the lines connecting the obstacle peak to path ends and the horizon in radian.

Figure 6.5 shows the diffraction loss for different values of ϑ when it is greater than -0.6, the related loss may be calculated from the following equation:

$$J(\vartheta)\ (\text{dB}) = 6.9 + 20\log\left(\sqrt{(\vartheta - 0.1)^2 + 1} + \vartheta - 0.1\right) \tag{6.21}$$

Despite being an approximation, knife-edge diffraction is widely used in practical situations using the methods described above. It provides a useful accuracy for diffraction due to terrain obstruction, despite the substantial differences between a theoretical knife-edge and actual hilltops.

6.2.6 Single Rounded Obstacles

The geometrical concept of a rounded obstacle is shown in Fig. 6.6. It should be noted that the distances d_1 and d_2 and height h all are measured to the vertex where the projected rays from TX and RX intersect above the obstruction. The diffraction loss for this obstacle may be calculated as

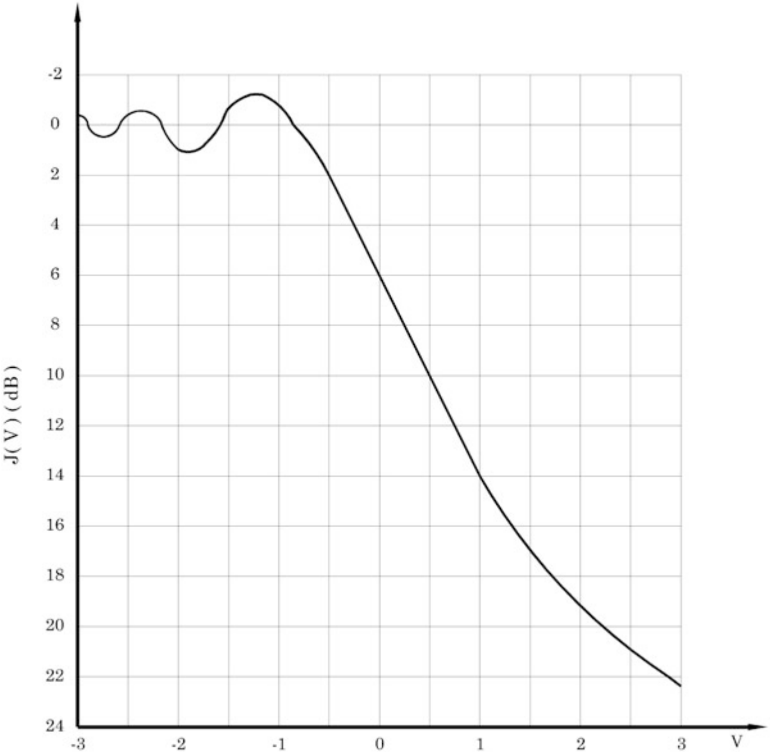


Fig. 6.5 Diffraction loss (Ref.: ITU-R, P.526)

$$A = J(\vartheta) + T(m, n) \tag{6.22}$$

$J(\vartheta)$ is equivalent knife-edge loss, while $T(m,\ n)$ is the additional loss due to the obstruction curvature. In practical units, ϑ can be expressed as

$$\vartheta = 0.0316h\left[\frac{2(d_1 + d_2)}{\lambda d_1 d_2}\right]^{1/2} \tag{6.23}$$

h and λ are in meters and d_1 and d_2 are in kilometers. The value of $J(\vartheta)$ according to the value of ϑ can be obtained from Fig. 6.6 or from Eq. (6.19).

The value of $T(m, n)$ can be obtained using the following equations:

$$T(m, n) = km^b \tag{6.24}$$

$$k = 8.2 + 12.0\,n \tag{6.25}$$

$$b = 0.73 + 0.27[1 - \exp(-1.43\,n)] \tag{6.26}$$

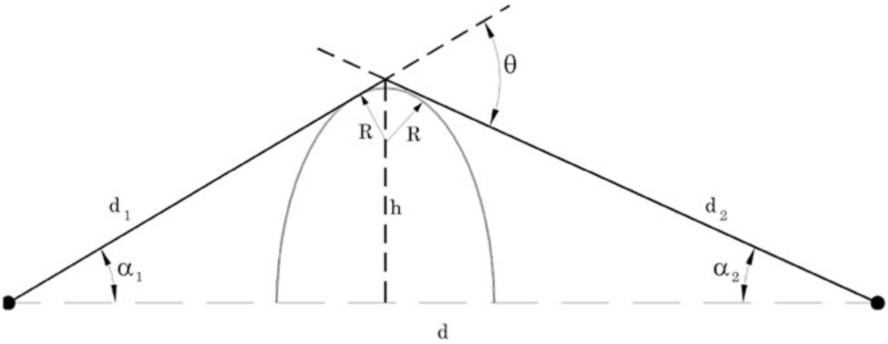


Fig. 6.6 Geometrical parameters of single rounded obstacle

$$m = R\left[\frac{d_1 + d_2}{d_1 d_2}\right] \bigg/ \left[\frac{\pi R}{\lambda}\right]^{1/3} \tag{6.27}$$

$$n = h\left[\frac{\pi R}{\lambda}\right]^{2/3} \bigg/ R \tag{6.28}$$

In these equations the R, d_1, d_2, h, and λ should have the appropriate units. In addition to using Eq. (6.22), the value of $T(m, n)$ can be obtained from Fig. 6.7 according to the values of m and n.

Example 6.3. There is a 20-m-high obstacle at distances of 4 and 6 km from the transmission path ends. Using 300 MHz radiowaves, find:

1. The ratio of obstacle height to first Fresnel radius.
2. The obstacle loss if it is a knife-edge type.
3. The obstacle loss if it is a rounded type of radius equal to 10 km.

Solution. 1.

$$f = 300\,\text{MHz} \quad \Rightarrow \quad \lambda = 1\,\text{m}$$

$$(L_1 = 4\,\text{km},\ L_2 = 6\,\text{km}) \Rightarrow r_1 = 48.99\,\text{m}$$

$$h/r_1 = 0.4$$

2. The knife-edge obstacle loss is

$$\lambda = 1\,\text{m} \quad \Rightarrow \quad \vartheta = 0.577$$

$$J(\vartheta) = 6.9 + 20\log(1.585) = 10.9\,\text{dB}$$

3. To calculate rounded obstacle loss, first $T(m, n)$ should be obtained.

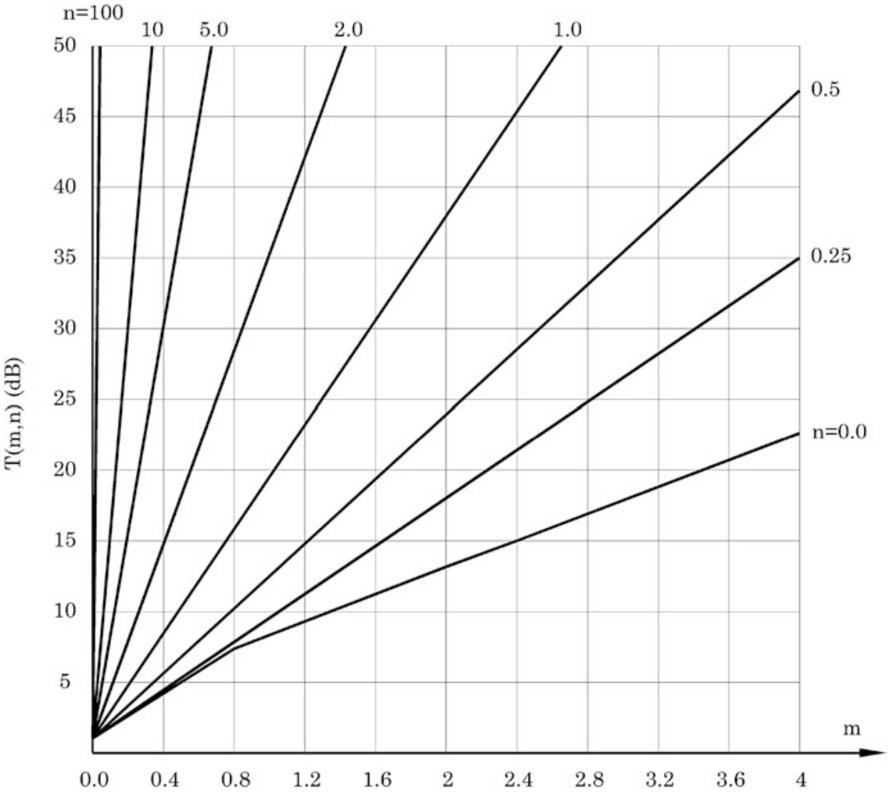


Fig. 6.7 $T(m,n)$ function in terms of m and n (Ref.: ITU-R, P.526)

$$(R = 10\,\text{km},\ \lambda = 1\,\text{m},\ h = 20\,\text{m}) \ \Rightarrow \ \text{m} = 0.13,\ n = 1.99$$

$$k = 8.2 + 12 \times 1.99 = 32.08, \quad \Rightarrow \quad b \approx 1$$

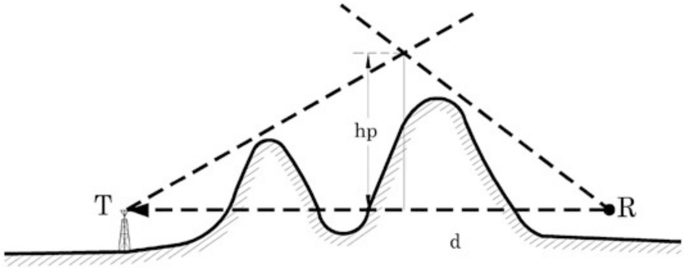
$$T(m,n) = 32.08 \times 0.13 = 4.17\,\text{dB}$$

$$A = J(\vartheta) + T(m,n) = 10.9 + 4.17 = 15.07\,\text{dB}$$

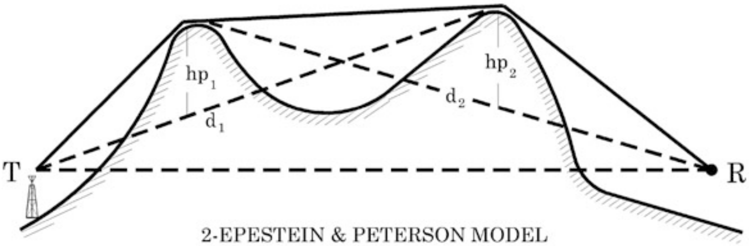
■

6.2.7 Double Isolated Obstacles

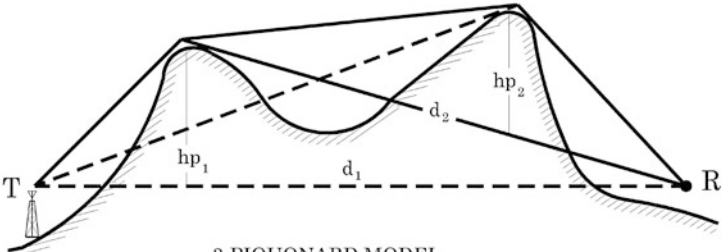
In most cases of mobile radio-communications, there are more than one obstacle in the propagation path. In the case of two obstacles, in some conditions, received signal level is greater than receiver threshold, and in spite of high attenuation it is detectable. To find a suitable calculation procedure for multiple obstructions, the



1-BULLINGTON MODEL



2-EPESTEIN & PETERSON MODEL



3-PIQUONARD MODEL

Fig. 6.8 Main models for calculation of double isolated obstacles

case was studied by a number of experts and several models suggested. As illustrated in Fig. 6.8, among a variety of models the following are more popular:

Bullington Model

As illustrated in Fig. 6.8 for the Bullington model, the inter-section of two tangential lines from transmitter (T) and receiver (R) antennas to their adjacent obstacles is assumed to be an equivalent knife-edge obstruction with height h_p. This model is applicable when the obstacles are near each other, and the obtained results are compatible to the experimental measurements.

Epstein and Peterson Models

As illustrated in Fig. 6.8 for this model, first, the h_{p1} and h_{p2} heights should be obtained and then the summation of their knife-edge losses should be calculated. This model is applicable when there is a long distance between the obstacles.

Piquonard Model

In this calculation method as illustrated in Fig. 6.8, first one of the obstacles is ignored, and the knife-edge loss is calculated according to h_{p1} and d_1. Then for the path between the first obstacle and the receiver, the second knife-edge obstacle loss is calculated according to h_{p2} and d_2. Finally the total loss which is the summation of both knife-edge obstacle losses is calculated. Comparing to the previous methods, this method is more appropriate with less limitations.

In this book, details of ITU-R method for calculating the double obstacle losses are also presented. The basics of this procedure are similar to loss calculation of single knife-edge obstruction. Figures 6.9 and 6.10 show two situations of obstacles from which, depending on obstacle height, the calculation method is selected.

This method consists of applying single knife-edge diffraction theory successively to the two obstacles, with the top of the first obstacle acting as a source for diffraction over the second obstacle.

As shown in Fig. 6.9, the first diffraction path, defined by the distances a and b and the height h'_1, gives a loss L_1 (dB). The second diffraction path, defined by the distances b and c and the height h'_2, gives a loss L_2 (dB). L_1 and L_2 are calculated using Eq. (6.21). A correction term L_c (dB) must be added to take into account the separation b between the edges. L_c may be estimated by the following expression:

$$L_c = 10 \log \left[\frac{(a+b)(b+c)}{b(a+b+c)} \right] \tag{6.29}$$

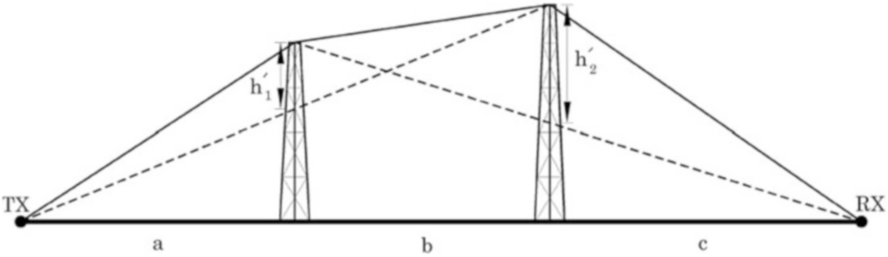


Fig. 6.9 Geometry of double isolated obstacles, type-1

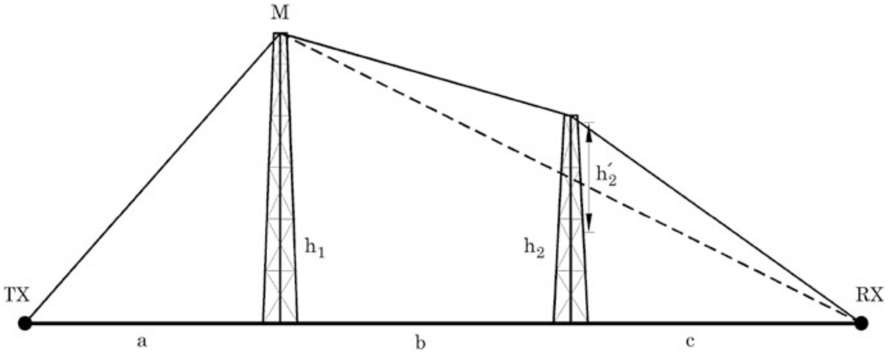


Fig. 6.10 Geometry of double isolated obstacles, type-2

which is valid when each one of L_1 and L_2 exceeds about 15 dB. Finally the total diffraction loss of these obstacles is calculated as follows:

$$L = L_1 + L_2 + L_c \tag{6.30}$$

The first method has a proper result in some cases which the value of L_1 and L_2 are almost the same.

According to Fig. 6.10, in the second method, one of the obstacles has more effects and is predominant. In this case, the first diffraction path is defined with parameters a, $(b + c)$, and h_1, and the second diffraction path is defined by parameters b, c, and h'_2, and their losses are derived using Eq. (6.21).

Correction factor T_c (dB) is estimated by the following expression:

$$T_c = \left[12 - 20\log\left(\frac{2}{1-\alpha/\pi}\right)\right] q/p^{2p} \tag{6.31}$$

$$p = \left[\frac{2(a+b+c)}{\lambda(a+b)c}\right]^{1/2} \times h_1 \tag{6.32}$$

$$q = \left[\frac{2(a+b+c)}{\lambda(a+b)c}\right]^{1/2} \times h_2 \tag{6.33}$$

$$\tan\alpha = \left[\frac{b(a+b+c)}{ac}\right]^{1/2} \tag{6.34}$$

And finally the total loss is derived from the following equation:

$$L = L_1 + L_2 - T_c \tag{6.35}$$

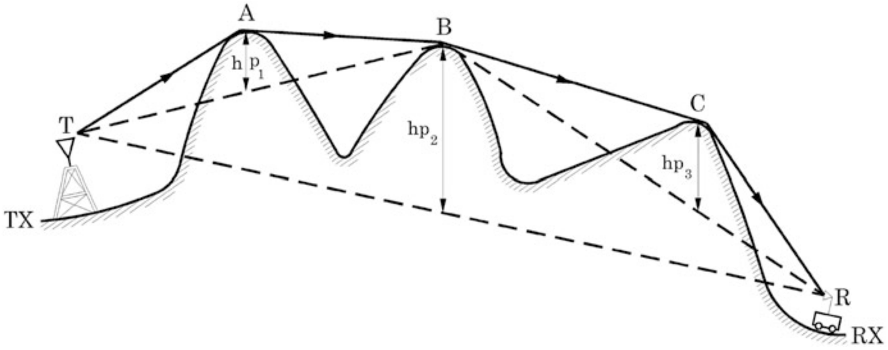


Fig. 6.11 Radio path with multiple obstructions

6.2.8 Multiple Isolated Obstacles

A number of authors have developed geometrical methods for modeling cascaded terrain obstructions as knife edges. Among them, the best one is known as Deygout model as illustrated in Fig. 6.11.

This method is based upon finding the point on the profile which, treated as a single knife-edge obstruction for the whole path (ignoring all other points), gives the highest value of v. This is the principal point and in Fig. 6.11 is point B. The corresponding diffraction loss is calculated for T-B-R. The path is then divided into two parts, one on each side of the principal point, and the process is repeated. Assuming that the secondary principal points are at A and C, diffraction losses are calculated for T-A-B and B-C-R and added to the total. This process is recursive and can be continued until there are no further significant points. In practice, it is normal to limit the process using a suitable criterion.

Example 6.4. Radiowave path profile is presented in Fig. 6.12. The heights of transmitter and receiver antennas are 2000 m and 2280 m, respectively, and the distance between them is 9.5 km. Calculate the diffraction loss of the obstacles for 150 MHz radiowaves. The obstacle heights are 2350 m and 2361 m, respectively.

Solution. Considering the profile, there are two knife-edge obstacles in the radiowave path. According to the ITU-R calculation method, the desired parameters of both paths are

$$h'_1 = 60\,\text{m}, d_2 = d'_1 = 2000\,\text{m}, d_1 = 259.6\,\text{m}, b = 2000\,\text{m},\ a = 250\,\text{m}$$

$$h'_2 = 80\,\text{m}, d'_2 = 7259\,\text{m}, d'_1 = 2000\,\text{m}, c = 7250\,\text{m},\ b = 2000\,\text{m}$$

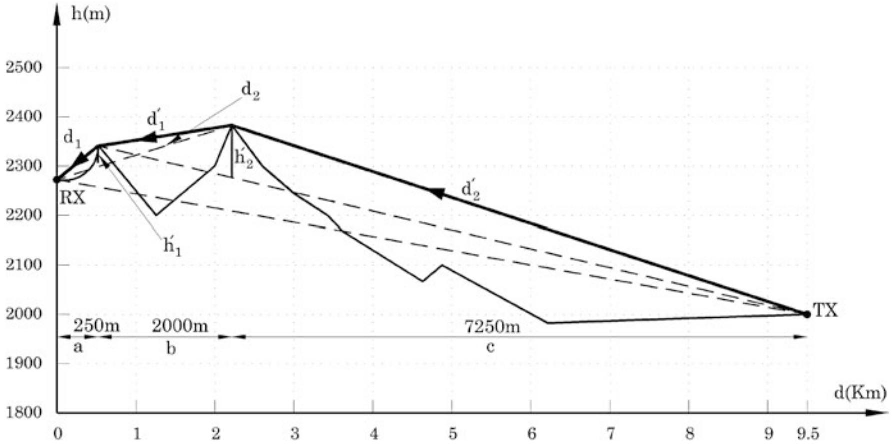


Fig. 6.12 Path profile for Example 6.4

Using Eqs. (6.21) and (6.35), the path diffraction loss is

$$\vartheta_1 = h_1' \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}\right) + \frac{1}{d_2}} \Rightarrow \vartheta_1 = 3.96 \Rightarrow L_1 = J(\vartheta_1) = 24.79\,\text{dB}$$

$$\vartheta_2 = h_2' \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1'}\right) + \frac{1}{d_2'}} \Rightarrow \vartheta_2 = 2.02 \Rightarrow L_2 = J(\vartheta_2) = 19.12\,\text{dB}$$

And the additional loss parameter according to Eq. (6.29) is derived as follows:

$$L_c = 0.39 \Rightarrow L = L_1 + L_2 + L_c = 44.3\,\text{dB}$$

■

6.3 Propagation Environment in Mobile Radio Communications

The propagated radiowaves from a terrestrial mobile radio station are affected by several mechanisms because of their special characteristics and applications while they are not experienced in other types of radio communications such as satellite and fixed radio systems or they are limited and may be ignored.

Generally, terrestrial attenuations are caused by the wave path structure and propagation environment. The low height of mobile antennas which are close to the Earth surface generates some additional losses due to adverse effects of wave propagation. The radio path structure causes their energy to be absorbed, attenuated, and scattered, and as a result, the signal level in the receiver is decreased. The summation of these losses and free-space loss result in the total path attenuation. Also mobile radiowaves are affected by different kinds of scattering, multipath mechanisms which cause deep fading in the received signals. These fading effects will appear in two formats with different statistical conditions:

- Long-term fading
- Short-term fading

Long-term fading is because of small changes in wave path structure, while the short-term fading is due to reflection from fixed and mobile objects. The radiowave propagation between the transmitter and receiver in wireless communications is severely affected by multipath fading phenomenon which is because of wave propagation near the Earth surface, while this mechanism is not considerable in sky and satellite communications.

Basically the transmitted signal level is attenuated continually in its path. In ideal conditions, this attenuation is just related to free-space loss, but in real situations, as explained in the next sections, there are several factors which increase this attenuation.

In wireless communications, sometimes the mobile station is moving and sometimes is fixed. In moving situations, it can move in different directions with different velocities, also each mobile station will face different kinds of scattering such as several moving objects. These scattering objects in the wave path will make a variable environment which depends on several parameters, and it could scatter, reflect, or even absorb the signal energy and will cause considerable variations in the received signal level. These changes would be studied statistically in terms of location and time variations, which delay spread is one of the adverse effects.

As explained, most of the affecting factors are variable and dynamic with stochastic natures, and finding analytical equations to model the mobile wave propagation is very complicated, so experts and designers usually prefer to use the experimental and statistical models for estimation of the received signal level and prediction of coverage area in the mobile radio networks. At the present time, the empirical models are accepted by international unions and professional authorities and applied using accurate procedures. A number of these applied models are popular and are given in this chapter. The ITU-R based model is discussed in the other chapter.

6.4 Signal Level Variability

6.4.1 Introduction

In mobile radio-communications, in addition to the direct waves, the receiver will detect some other waves because of some phenomena like diffraction, reflection, and refraction. Accordingly, the stochastic nature of these phenomena, the received

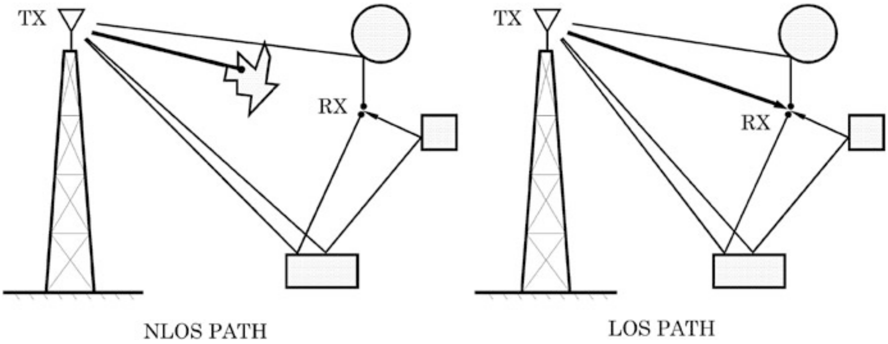


Fig. 6.13 Main types of reception in mobile radio network

signal level, will vary with location and time. The received signal quality depends on several factors such as transmission environment, frequency, time delay, modulation types, and also undesirable radiowaves and frequency interference.

6.4.2 Shadow

As it was shown in Fig. 6.13, in some cases, there is an obstacle which prohibits receiving the direct waves in the receiver, and actually receiver is in radiowave shadow.

These obstacles can be natural such as mountains, hills, and forests or artificial like buildings, metallic structures, and moving obstacles. If the obstacle shape, material, and dimensions are known, they can be analyzed using the proper electromagnetic models and equations, but in most cases, because of the obstacle variety and also their time changing, the theoretical methods are not applicable, so the experimental equations shall be employed.

6.4.3 Location Variability

In wireless networks, the received signal level in the mobile station will vary continually or randomly with location changes. Area coverage prediction methods are required to provide the statistics of reception conditions for a given area, rather than at any particular point. Usually affecting factors are categorized in the following five major groups:

- **Multipath Fading**

  Signal variations will occur over scales of the order of wavelength due to phasor summation of multipath effects, e.g., reflections from the ground, man-made structures, buildings, etc.
- **Local Ground**

  Received signal level will vary due to obstruction by ground cover in the local vicinity, e.g., buildings, trees, etc., over scales of the order of the sizes of such objects. Normally, local ground cover effects are more than multipath variations.
- **Terrain Structure**

  Signal variations will also occur due to changes in the terrain structure and geometry along the entire propagation path, e.g., the presence of hills, mountains, lakes, etc. For all except very short paths, the scale of these variations will be significantly larger than other types of variations.
- **Mobility Conditions**

  Mobility of handheld and vehicular units in the mobile radiocommunications including land, maritime, and aeronautical systems results in some adverse effects such as decrease of antenna and system gains, non-line-of-sight links, and Doppler effect which all of them make lower grade of service or performance degradation.
- **Unbalanced Radio Links**

  In the mobile radio networks, different types of equipment are used for three main types of radio stations, i.e., handheld, vehicular, and base units. Major differences include:

  - Transmitter output power
  - Receiver sensitivity in static and dynamic conditions
  - Antenna gain
  - Antenna space diversity reception

  Thus, uplinks and downlinks are not in balance conditions forming different coverage areas for handheld or vehicular radio units.

In wireless communications in VHF and UHF bands, location variations are usually measured in a square area with 100- to 200-m side. Signal level distribution in urban area has almost log-normal distribution. Also since multipath fading has frequency selective nature, so identifying the signal effective bandwidth is necessary in its analysis.

Field strength at the receiving location, E_q, for $q\,\%$ of time can be calculated by

$$E_q\ [\mathrm{dB}\,\mu\mathrm{V/m}] = E_m[\mathrm{dB}\,\mu\mathrm{V/m}] + Q_i(q/100)\cdot\sigma_L\ \ [\mathrm{dB}] \tag{6.36}$$

where:

Q_i: Log-normal distribution coefficient according to Table 6.1
σ_L: Standard deviation in dB
E_m: Median received signal level in $\mathrm{dB}_{\mu\mathrm{V}}/\mathrm{m}$

Table 6.1 Inverse complementary cumulative normal distribution values (Ref.: ITU-R, P.1546)

q (%)	$Q_i(q/100)$	q (%)	$Q_i(q/100)$	q (%)	$Q_i(q/100)$	q (%)	$Q_i(q/100)$
1	2.327	26	0.643	51	-0.025	76	-0.706
2	2.054	27	0.612	52	-0.050	77	-0.739
3	1.881	28	0.582	53	-0.075	78	-0.772
4	1.751	29	0.553	54	-0.100	79	-0.806
5	1.654	30	0.524	55	-0.125	80	-0.841
6	1.555	31	0.495	56	-0.151	81	-0.878
7	1.476	32	0.467	57	-0.176	82	-0.915
8	1.405	33	0.439	58	-0.202	83	-0.954
9	1.341	34	0.412	59	-0.227	84	-0.994
10	1.282	35	0.385	60	-0.253	85	-1.026
11	1.227	36	0.358	61	-0.279	86	-1.080
12	1.175	37	0.331	62	-0.305	87	-1.126
13	1.126	38	0.305	63	-0.331	88	-1.175
14	1.080	39	0.279	64	-0.358	89	-1.227
15	1.036	40	0.253	65	-0.385	90	-1.282
16	0.994	41	0.227	66	-0.412	91	-1.341
17	0.954	42	0.202	67	-0.439	92	-1.405
18	0.915	43	0.176	68	-0.467	93	-1.476
19	0.878	44	0.151	69	-0.495	94	-1.555
20	0.841	45	0.125	70	-0.524	95	-1.645
21	0.806	46	0.100	71	-0.553	96	-1.751
22	0.772	47	0.075	72	-0.582	97	-1.881
23	0.739	48	0.050	73	-0.612	98	-2.054
24	0.706	49	0.025	74	-0.643	99	-2.327
25	0.674	50	0.00	75	-0.674		

For calculating the standard deviation, the ITU-R recommendation P.1546 is used for digital signals with bandwidth less than 1 MHz and also analog signals which suggest the following equation:

$$\sigma_L\ [\mathrm{dB}] = K + 1.6 \log f\ [\mathrm{MHz}] \tag{6.37}$$

In the above equation, value of constant K is selected as follows:

- $K = 2.1$ for wireless systems in urban areas
- $K = 3.8$ for wireless systems in suburban areas
- $K = 5.1$ for analog broadcasting systems

For digital systems with bandwidth equal or greater than 1 MHz, the standard deviation is equal to 5.5 dB for all frequencies. Table 6.2 shows the standard deviation values for different frequency bands and conventional radiocommunications.

Table 6.2 Location variability standard deviation (Ref.: ITU-R, P.1546)

Frequency range	30–300 MHz	300–1000 MHz	1000–3000 MHz
Nominal frequency (MHz)	100	600	2000
Broadcasting analog	8.3	9.5	–
Broadcasting, digital	5.5	5.5	5.5
Mobile, urban	5.3	6.2	7.5
Mobile, suburban, rolling hills	6.7	7.9	9.4

Also, the following equations are suggested for standard deviation according to the ITU-R recommendation P.1406:

- For rural and suburban areas

$$\sigma_L\ [\text{dB}] = 6 + 0.69\left(\frac{\Delta h}{\lambda}\right)^{1/2} - 0.0063\left(\frac{\Delta h}{\lambda}\right), \quad \frac{\Delta h}{\lambda} \leq 3000 \tag{6.38}$$

$$\sigma_L\ [\text{dB}] = 25, \quad \frac{\Delta h}{\lambda} > 3000 \tag{6.39}$$

  In the above equations, Δh is the path interdecile height variation and λ is wavelength, both in meters.

- For flat urban areas in range of 100–300 MHz

$$\sigma_L\ [\text{dB}] = 5.25 + 0.42\log(f/100) + 1.01\log^2(f/100) \tag{6.40}$$

- In general for UHF band and distances which are less than 50 km

$$\sigma_L\ [\text{dB}] = 2.7 + 0.42\log(f/100) + 1.01\log^2(f/100) \tag{6.41}$$

- Normally, in mobile radio networks for link design calculations, the following criteria shall be considered:

$$\sigma_L\ [\text{dB}] = 8\,\text{dB}, \quad 30\,\text{MHz} \leq f < 300\,\text{MHz} \tag{6.42}$$

$$\sigma_L\ [\text{dB}] = 10\,\text{dB}, \quad 300\,\text{MHz} \leq f < 3000\,\text{MHz} \tag{6.43}$$

Example 6.5. Suburban mobile radio systems in 450 MHz band are designed to have 90 % location coverage. To increase the coverage area to 95 %, how much the antenna gains should be increased?

Solution. According to Eq. (6.37), the following results are derived:

$$\sigma_L = 3.8 + 1.6\log(450) \Rightarrow \sigma_L = 8.045\,\text{dB}$$

$$\text{FM}(90\,\%) = Q_i(90\,\%) \times \sigma_L = 1.282 \times 8.045 = 10.314$$

$$\text{FM}(95\,\%) = Q_i(95\,\%) \times \sigma_L = 1.645 \times 8.045 = 13.234$$

$$\Delta(\text{FM}) = 2.92\,\text{dB}$$

So the new antenna gain is about 3 dB greater than existing antenna gain. ■

Table 6.3 Time variability standard deviation (σ_t) in dB (Ref.: ITU-R, P.1406)

Frequency band	Distance (km)	50	100	150	175
VHF	Land and sea	3	7	9	11
UHF	Land	2	5	7	–
	Sea	9	14	20	–

6.4.4 Time Variability

Received signal level in addition to location variability includes some time variations, which have statistical nature and are mostly due to climate condition variability and motion. The time variability standard deviation value is represented by σ_L which is a function of the following parameters:

- Distance between the transmitter and receiver
- Terrain structure along radio path
- Working frequency band

In Table 6.3, σ_t value is given for VHF and UHF in the mobile radio-communications.

6.4.5 Location and Time Variability

If ρ is the correlation coefficient between location and time variability, then combined standard deviation value is calculated from the following equation:

$$\sigma = \sqrt{{\sigma_L}^2 + {\sigma_t}^2 + 2\rho\sigma_L\sigma_t} \tag{6.44}$$

According to the low correlation between these random processes, ρ is usually neglected.

$$\sigma = \sqrt{{\sigma_L}^2 + {\sigma_t}^2} \tag{6.45}$$

Example 6.6. Signal level in 50 % of locations within an area equal to 200 × 200 m^2 is acceptable. Assuming 5 W transmitter, $\sigma_L = 8$ dB, and ignoring the time variability, obtain the following parameters:

1. Fade margin (FM) for received signal level in acceptable conditions for at least 90 % of locations.
2. For 97 % location coverage, what is the new required transmitter power?

Solution. 1. Using Table 6.1,

$$Q_i(90\,\%) = 1.282$$

$$\text{FM} = Q_i.\sigma_L = 10.256\,\text{dB}$$

2.

$$\begin{aligned} q' &= 97 \quad \Rightarrow \quad Q_i(97\,\%) = 1.881 \\ \text{FM}' &= Q_i(97\,\%) \cdot \sigma_L = 15.048\,\text{dB} \\ 10 \log \left(\frac{P_t'}{P_t} \right) &= \text{FM}' - \text{FM} = +4.792\,\text{dB} \\ P_t' &= P_t \times \text{Antilog}\, 0.4792 \approx 15\,\text{W} \end{aligned}$$

■

6.4.6 Fade Margin

The received signal level equations and tables presented by authorized agencies such ITU-R are based on the median values, which are 50 % location and 50 % time coverage. However in practice much more coverage is required. For instance, 95 % location and 90 % time coverage is a normal request.

To receive the desirable signal in greater than 50 %, some additional value called fade margin is required in design calculation as follows:

Step 1: Calculate the values of σ_L and σ_t using Tables 6.2 and 6.3 or using relevant equations.
Step 2: Calculate the value of σ using Eq. (6.45).
Step 3: For given q, the $Q_i(q/100)$ coefficient value is obtained from Table 6.1.
Step 4: Calculate the fade margin (FM) in dB using the following equation:

$$\text{FM} = Q_i(q/100) \cdot \sigma \tag{6.46}$$

In other words, the received signal level should be greater than the median signal level calculated in receiver at least equal to fade margin (FM) for receiving radiowaves with better coverage than median value (50 %).

Example 6.7. For urban mobile radiocommunications in VHF and low UHF bands and at 50 km distance, find:

1. σ_L and σ_t
2. The total standard deviation value assuming that there is no correlation between location and time standard deviations

Solution. 1. For VHF band, using Tables 6.2 and 6.3,

$$\sigma_L = 5.3\,\text{dB}, \quad \sigma_t = 3\,\text{dB}$$

Also for low UHF band, or $300 < f < 1000$ MHz, using the mentioned tables,

$$\sigma_L = 6.2\,\text{dB}, \quad \sigma_t = 2\,\text{dB}$$

2. The total standard deviation values are

$$\sigma_{\text{VHF}} = \sqrt{\sigma_L{}^2 + \sigma_t{}^2} = 6.1\,\text{dB}$$
$$\sigma_{\text{UHF}} = 6.5\,\text{dB}$$

■

6.5 Polarization

6.5.1 Depolarization Effects

Different kinds of polarization like linear and circular polarizations could be used in mobile radio-communications. In terrestrial applications of the mobile radio-communications, electromagnetic waves will deviate from their original polarization because of some phenomena like diffraction and reflection. The depolarization effects may be taken into account by defining a new factor called cross polarization discrimination(CPD). The measurements performed under ITU-R supervision at 900 MHz frequency indicate the following points:

- XPD is not highly dependent on the radio path length.
- The average value of XPD in rural and residential areas is about 5–8 dB and in open areas is greater than 10 dB.
- The average correlation between horizontal and vertical polarization is almost zero.
- The XPD value is in inverse relation with frequency, and its value in VHF band is greater than its value in UHF band. The XPD is equal to 18 dB at 35 MHz frequency.
- The XPD in 30–1000 MHz frequency range has a log-normal distribution. The standard deviation depends on frequency and its average value (10–90 %) is about 15 dB.

Due to depolarization phenomenon, two kinds of time variability are observed. The first one is slow variability resulting from the Earth electric characteristics variations due to weather conditions which is mostly considerable in low frequencies. The second one is because of trees resulting in the signal amplitude attenuation up to few decibel.

6.5.2 Polarization Diversity

Because of low XPD value in mobile radio-communications in the VHF and UHF frequency bands and suffering the loss of some significant portion of the radiated power in rural and residential areas, polarization diversity may be used to improve received signal quality. One of the common methods is to employ two linear orthogonal polarizations (such as horizontal and vertical polarizations) in a mobile radio fixed station. Another solution is to use circular polarization in fixed station and linear polarization in mobile station. However, the latter case will result in 3 dB more attenuation because of mismatching, but it has some positive effects in the received signal stability.

6.6 Antenna Height

6.6.1 Outlines

In mobile radio-communications, the received signal level variations depend on transmitter and receiver antenna height. Usually, antenna gain increases with higher antenna height, but in some cases, in spite of increasing the antenna height, because of non-proper antenna position selection, the received signal level might decrease. If there is no local clutter, direct waves could be combined with reflected waves from the Earth surface. The received signal level variation in vertical direction includes peak points based on terrain geometrical conditions.

In mobile receivers, because of clutter and other reflected waves, the two-wave model (direct and reflected waves) is not valid, especially in frequencies greater than 200 MHz. Increasing the antenna height will decrease the clutter loss and therefore leading to higher received signal level in the receiver.

According to this fact and also the relation between antenna height and clutter loss values, it could be concluded that antenna height gain is related to terrain surface nature. Consequently, in some coverage estimation models, considering the information about terrain nature and structure along the radio path, antenna height gain is directly related to clutter loss calculation.

For BTS stations in open areas like suburbs and working at frequency less than 200 MHz, the negative effects of two-wave model (direct and reflected waves) is considerable, so by changing the antenna height, these undesirable effects should be decreased. It is very difficult to estimate this phenomenon accurately, and complete information about terrain structure along the radio path is needed. Due to short wavelength in frequencies which are more than 200 MHz, the effects of this mechanism are negligible.

6.6.2 Antenna Height Gain

In VHF and UHF wireless communications, path loss is affected by transmitter and receiver antenna heights. As mentioned before, for two-wave model, the received field is derived from the following equation:

$$\bar{E}_s = [1 + \Gamma e^{j\beta(\Delta d)}] \cdot \bar{E} \tag{6.47}$$

In this equation, vector E is direct received field in receiver location and Γ is reflection coefficient of terrain surface and Δd is the difference between direct and reflected path lengths. Due to free-space loss, the value of $\bar{E}$ is in inverse relation with distance, which is expressed by

$$|E|^2 \propto \frac{1}{(d/\lambda)^2} = (d/\lambda)^{-2} \tag{6.48}$$

According to these conditions and also the equation for wave propagation in free space (Ferris equation), the average signal power in receiver is derived as follows:

$$P_r = \frac{|E|^2}{2\eta_\theta} = P_t \cdot G_t \cdot G_r \left(\frac{4\pi d}{\lambda}\right)^{-2} \tag{6.49}$$

P_r: Transmitter power
G_t, G_r: Transmitter and receiver antenna gain
η_θ: Free-space intrinsic impedance

Assuming two-wave model, the difference between direct and reflected waves could be represented as follows:

$$\Delta\Psi = \beta \cdot \Delta d \tag{6.50}$$

As mentioned before in Chap. 2, assuming that the heights of transmitter and receiver antennas are very small in comparison with their distance, the following equation is concluded:

$$\Delta d \approx \frac{2h_t \cdot h_r}{d} \tag{6.51}$$

Also considering the actual conditions of the terrestrial communications, the following approximations are made:

$$\sin \Delta\Psi \approx \Delta\Psi = \frac{4\pi h_t \cdot h_r}{\lambda \cdot d} \tag{6.52}$$

$$\begin{aligned} P_r = \frac{|\bar{E}_s|^2}{2\eta_\theta} &= P_t \cdot G_t \cdot G_r \cdot \left(\frac{4\pi d}{\lambda}\right)^{-2} \cdot |1 - \cos\Delta\Psi - j\sin\Delta\Psi|^2 \\ &\approx P_t \cdot G_t \cdot G_r \cdot \left(\frac{4\pi d}{\lambda}\right)^{-2} \cdot (\Delta\Psi)^2 \\ &\approx P_t \cdot G_t \cdot G_r \cdot \left(\frac{h_t \cdot h_r}{d^2}\right)^2 \end{aligned} \tag{6.53}$$

Although (6.53) is an approximate formula neglecting frequency effects, it is accurate enough to be used in mobile radio calculations.

In accordance with Eq. (6.53) and assuming fixed values for distance (d), gain of antennas ($G_t,\ G_r$), and transmitter output power (P_t), the relative overall antenna height gain is

$$\Delta G = \left(\frac{h'_t \cdot h'_r}{h_t \cdot h_r}\right)^2 \tag{6.54}$$

$$\Delta G\,[\text{dB}] = 20\log(HR_t) + 20\log(HR_r) \tag{6.55}$$

In this equation, HR_t and HR_r indicate ratio of transmitter and receiver ultimate antenna heights to their initial values, respectively.

Example 6.8. Find the path length relative loss value and also transmitter antenna height gain assuming that the other parameters will be unchanged.

Solution. For path length changes

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{h_t \cdot h_r}{d^2}\right)^2$$

$$P'_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{h_t \cdot h_r}{d'^2}\right)^2$$

$$\Rightarrow \frac{P'_r}{P_r} = \left(\frac{d}{d'}\right)^4 \Rightarrow L = 40\log\frac{d'}{d}$$

So path loss has the changing rate of 40 dB/dec. Also in general case for transmitter and receiver antenna heights

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{h_t \cdot h_r}{d^2}\right)^2$$

$$P'_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{h'_t \cdot h'_r}{d^2}\right)^2$$

$$\Rightarrow \frac{P'_r}{P_r} = \left(\frac{h'_t \cdot h'_r}{h_t \cdot h_r}\right)^2 \Rightarrow \Delta G = \left(\frac{h'_t \cdot h'_r}{h_t \cdot h_r}\right)^2$$

■

In the case that the receiver antenna height is fixed, transmitter antenna height gain is equivalent to

$$\Delta G\,[\mathrm{dB}] = 20 \log\left(\frac{h'_t}{h_t}\right) \tag{6.56}$$

According to this equation, BTS antenna height gain will have the variation rate equal to 20 dB/dec or 6 dB/oct.

6.6.3 Fixed Antenna Height Gain

Usually in wireless communications, the fixed stations are located in high places or on tower top. As mentioned in the previous section, increasing the antenna height will result in the higher signal level in the receiver. By increasing the antenna height from h to $2h$, then its height gain will be 6 dB.

Example 6.9. In mobile radio-communications, it is required to increase the received signal level in mobile receiver by 5 dB; find:

1. Transmitter ultimate antenna height if its initial value is 20 m.
2. The ratio of new received power to its initial value.

Solution. 1.

$$\Delta G\,[\mathrm{dB}] = 20 \log\left(\frac{h'_t}{h_t}\right) = 5\,\mathrm{dB}$$

$$h'_t = h_t \times \mathrm{Antilog}\left(\frac{1}{4}\right) = 35 \cdot 56 \approx 36\,\mathrm{m}$$

2.

$$\frac{P'_r}{P_t} = \left(\frac{h'_t}{h_t}\right)^2 \Rightarrow \frac{P'_r}{P_t}$$

■

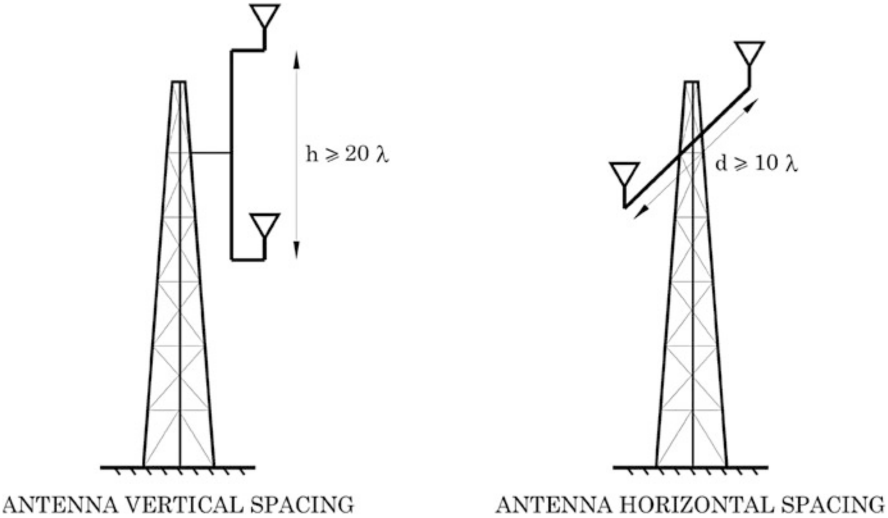


Fig. 6.14 Vertical and horizontal antenna space diversity

One of the suitable methods to improve quality of received signal level in mobile radio networks is using antenna space diversity which could be employed in vertical and horizontal types. This technique could be appropriate in fixed stations, but it is not practical to apply this technique in handset and vehicle receivers. As it is shown in Fig. 6.14, using the vertical antennas is helpful when the distance between them is about 20λ or more, but in horizontal antennas, it should be around 10λ.

Example 6.10. Find the minimum effective antenna distance for GSM systems in 1800 MHz band.

Solution.

$$\begin{aligned} f = {} & 1800\,\text{MHz} \quad \Rightarrow \quad \lambda = 0.167\,\text{m} \\ h_v \geq {} & 20\lambda \quad \Rightarrow \quad h_v \geq 3.34\,\text{m} \\ d_h \geq {} & 10\lambda \quad \Rightarrow \quad d_h \geq 1.67\,\text{m} \end{aligned}$$

■

6.6.4 Mobile Antenna Gain

Since in the mobile radio-communications, the handset and vehicle antennas are used in low heights operating in multipath propagation conditions, therefore, in most cases, the antenna gain is less than the maximum available value according to its propagation pattern. Even in line-of-sight radio links, the angle of arrival could be around 10°.

In this case, the received signals may be received in zero point or side lobes instead of receiving in the main lobe. Several experiments indicated that mobile antennas of 3–5 dB maximum gain operate with an effective gain of 1.5 dB in working conditions.

6.7 Reflection and Multipath

6.7.1 Local Reflections

As depicted in Fig. 6.15, in addition to direct waves, mobile receiver will receive some waves reflected from the Earth surface or other nearby objects like buildings, trees, or fixed and mobile structures. The reflected waves are similar to the main wave with random phase and amplitude, so they could cause some positive or negative changes in the main received signal level.

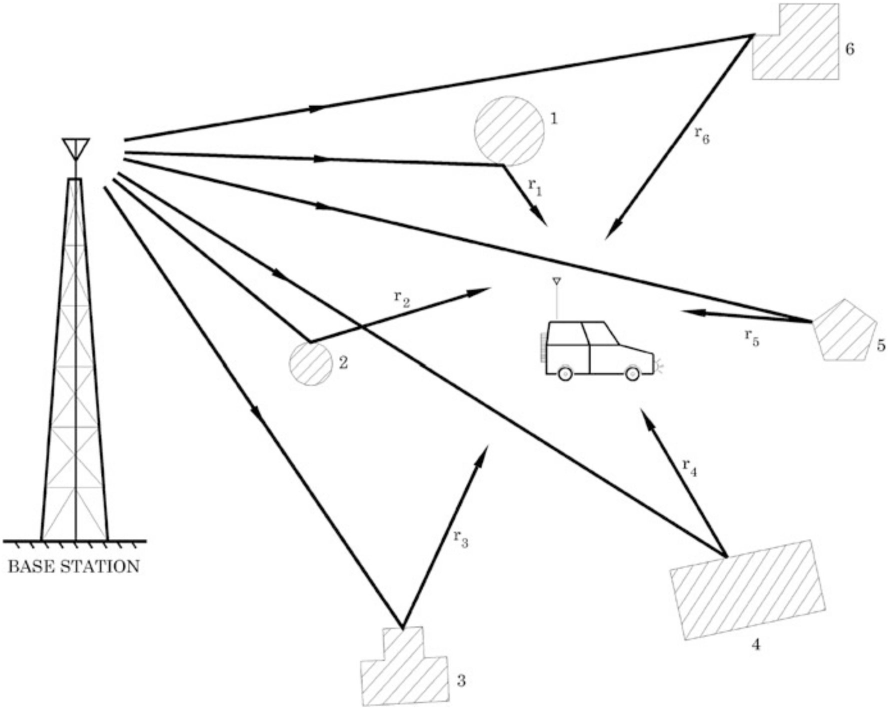


Fig. 6.15 Local reflections and multipath reception

The interference between the main and reflected waves cause some instant variations in the received signal phase and amplitude resulting in interference pattern in which the distance between the minimum points (or the maximum points) is at least equal to $(\lambda/2)$. There are several reflections in urban and forest areas, so the instant received signal level in far fields ($d \gg 10\,\lambda$) has a Rayleigh distribution.

The interference algorithm in mobile receivers has a fast rise, even in fixed locations which receive reflections from mobile vehicles. So in these conditions, fading could be about or more than 30 dB greater than average signal level. In some cases, for example, when the receiver is in shadow location, the local reflections could improve receiving signal qualities.

6.7.2 Correlation Between Main and Unwanted Signals

Correlation between average values of received signals from different sources is important in calculation of the carrier-to-interference ratio (C/I). Assuming that carrier average power value is equal to C_m in terms of decibel with standard deviation of σ_C, and also interference source average power is equal to I_m in terms of decibel with standard deviation of σ_I, then non-correlation condition, $\rho = 0$, yields

$$(C/I)_m = C_m - I_m \tag{6.57}$$

$$\sigma_{C/I} = \sqrt{\sigma_C^2 + \sigma_I^2} \tag{6.58}$$

In case of correlation coefficient $\rho \neq 0$, then

$$\sigma_{C/I} = \sqrt{{\sigma_C}^2 + {\sigma_I}^2 - 2\rho\sigma_C\sigma_I} \tag{6.59}$$

In a special case, which $\sigma_C = \sigma_I = \sigma$, this equation could be simplified as follows:

$$\sigma_{C/I} = \sigma\sqrt{2(1-\rho)} \tag{6.60}$$

Several experiments and studies about the correlation coefficient of received power indicate that in the case of receiving from several directions, the correlation coefficient is very small. If the difference between the arrival to antenna is very small, then the correlation coefficient (ρ) is considerable and its value for sources which are near the forest and agriculture areas is about 0.8–0.9 and in urban areas is about 0.4–0.8. This value is very small in mountainous areas.

6.7.3 Multipath Fading

Multipath fading has considerable effects on the amplitude, frequency, and phase of carrier signal in mobile communications. The carrier signal can be defined simply by

$$S_0(t) = a_0 \cos(\omega_0 t + \phi_0) = R_e \cdot a_0 \exp[j(\omega_0 t + \phi_0)] \tag{6.61}$$

The multipath fading shown in Fig. 6.14 can be studied in the following three basic cases:

- Static case when the mobile station and other nearby transmitters are fixed
- Semi-dynamic case when the mobile station is fixed but other nearby transmitters are moving
- Dynamic case: when the mobile station and other nearby transmitters are moving

Due to Doppler effect, in dynamic case, a new frequency denoted by f_d and defined by the following equation should be considered:

$$f_d = f_m \cos\theta, \quad f_m = \frac{V}{\lambda} \tag{6.62}$$

According to Fig. 6.16, in the above equation, f_m is the maximum Doppler frequency, θ is the angle between wave path and direction of mobile motion, V is mobile relative velocity, and λ is wavelength.

Because of fading in multipath propagation, each one of these three main parameters of the signal may be changed. In some cases, this fading could be a selective type.

6.8 Time Delay Spread

6.8.1 Received Signal Time Delay

In mobile communications, due to receiving signal from a number of directions with different time delays comparing with received signal from the main path, the time delay spread will occur. For a better description of this phenomenon, considering Fig. 6.17, assume an impulse signal $S_0(t) = a_0\delta(t)$ is transmitted. After this signal passed through different paths, some different impulse signals will be received in different times by the receiver; thus, the total delay will spread effectively. This phenomenon is similar to reflection of voice in a mountainous area.

The received signal in the receiver could be expressed with the following equation:

$$S(t) = a_0 \sum_{i=0}^{n} a_i \delta(t - \tau_i) \cdot e^{i\omega t} = E(t) \cdot e^{i\omega t} \tag{6.63}$$

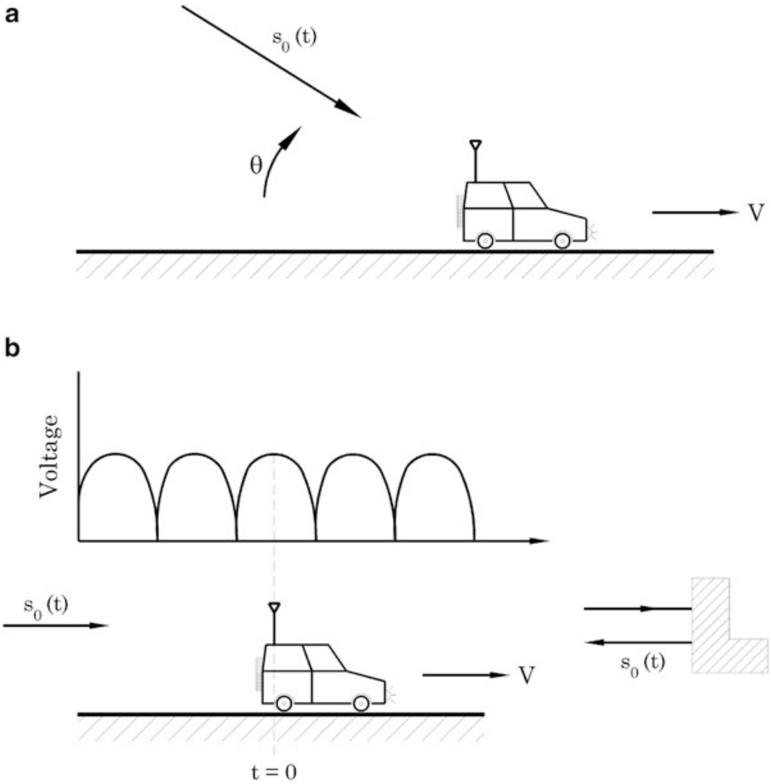


Fig. 6.16 Doppler effect in mobile communications

According to this equation, each signal will be received in the receiver in terms of an impulse signal with ω frequency. Therefore, by increasing the number of nearby transmitters, the received signal numbers will increase accordingly and it would be in terms of a pulse with length Δ which is called delay spread. In general, signals with shorter path length will be received with more power, but some-times this is not true because of different materials of natural or man-made structures.

Time spread delay will determine the required time interval between transmitting different signals to avoid the inter-symbol interference (ISI). This value should be smaller than symbol transmitting time.

Most of radio systems, specially the digital ones, are sensitive to multipath reflections. In this case, in addition to the direct received signals, some reflected versions of the main signal will be received with different time delays in the receiver. The effects of reflected waves appear mostly in amplitude and time delay parameters of them. In this case, the most important parameter is root mean square (RMS) of delay spread denoted by S. Usually $2S$ is a criterion for multipath time delay spread:

$$T_m = 2S \tag{6.64}$$

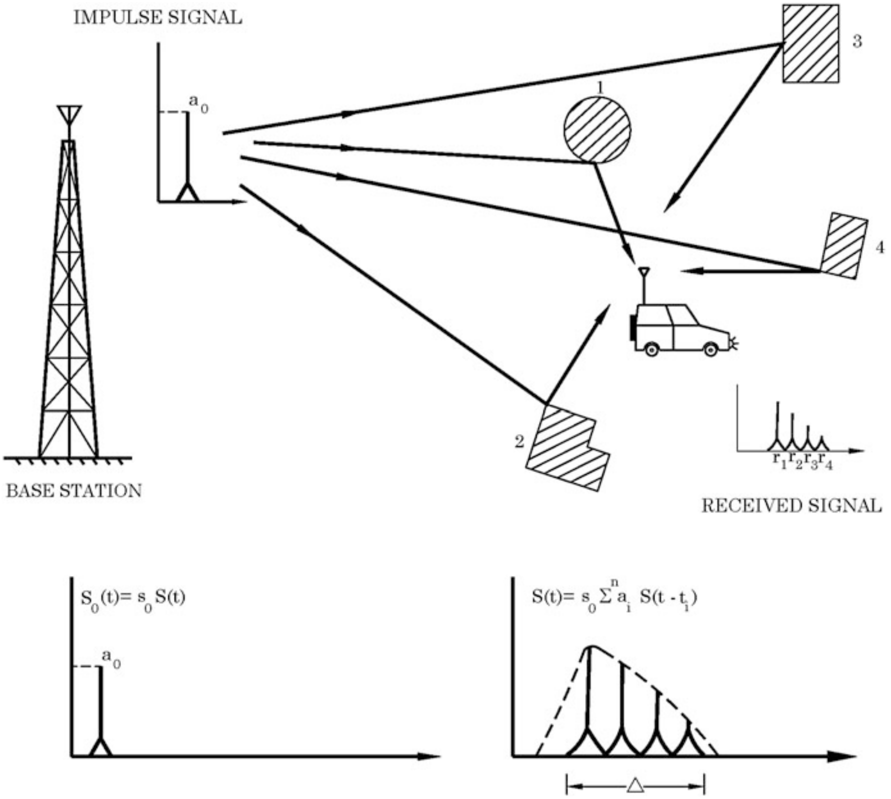


Fig. 6.17 Time delay spread in receiver

This parameter is usually considered in the evaluation of mobile radio-system performance and is a criterion to compare different modulation methods and measure the effect of T_m in them.

6.8.2 System Performance

In digital communications, based on ratio of delay spread over one symbol time interval, some different classifications are defined for bit error rate (BER). For instance, in differential phase shift keying (DPSK) modulation, phase variations will cause some irreducible errors which will exist even for large signal-to-noise ratio.

In the case that S value is small in comparison with symbol time interval, the irreducible bit error rate is mostly due to delay spread and is not related to origin and exact shape of impulse response; however, in the case that the S value is greater than symbol time interval, the inter-symbol interference should be considered which is related to impulse response shape.

6.9 Climate Effects

The effects of weather and climate variations, due to the air particles like oxygen, nitrogen, and other Earth atmosphere gases, fogs, dust, and also special gases in industrial areas, will be considered. Rain, snow, hail, humidity, temperature, and fog are additional items with different effects on the climate variations.

If radiowaves are propagated in the free space, they just may be affected by attenuation of diffraction. But in the case that these waves are propagated in Earth surface or atmosphere, they will be affected with several mechanisms such as magnetic storms, sky noises, sun-spots, and also atmospheric events like rain, cloud, snow, hail, fog, humidity, and wind or terrestrial parameters like mountains, forests, and seas.

6.9.1 Index of Refraction

Generally, the Earth atmosphere will be more diluted in terms of the height increase; in other words, the index of refraction will be reduced. Variation of the refraction index is usually continuous and it will cause the smooth waves curvature. In case of assuming a direct path for wave propagation, a modified Earth radius shall be considered. According to air index of refraction variations in standard conditions, the effective Earth radius is about 8500 km (for complete explanation, refer to Chap. 3).

Ratio of effective Earth radius to its real value is effective Earth radius factor and it is expressed with K-factor which is about 1.33 for the standard conditions. Due to some natural phenomena, the effective Earth radius is reduced and even sometimes is less than real Earth radius. This situation, which is equivalent to K-factor value of less than 1, causes high bulge on Earth surface, and it would be an obstacle for radiowave propagation near the Earth surface.

6.9.2 Climate Factors

Some important climate factors and their effects in VHF and UHF wireless communications are as follows:

- **Atmospheric Particles**
  - Oxygen, nitrogen, and other natural gases are not effective on the wave propagation in mobile radio bands.
  - Water vapor, fog, and air dust due to small dimensions compared to the wavelength of VHF and UHF bands are not effective in wave propagation.

  - Wind produced by the motion of atmospheric molecules has some positive effects on wave propagation by making a well-mixed and homogeneous medium. As a result of wind, standard atmosphere will be formed and air ducts will disappear.

- **Atmospheric Precipitation**

  Atmospheric precipitations such as rainfall, snow, and hail do not have tangible effects on amplitude attenuation and reflection in VHF and UHF band wave propagation.

- **Main Effects**

  - Duct will be formed because of settlement of intense layer in upper height and creation of a channel between the Earth and intense layer or settlement of a dilute layer between the two intense layers producing an air duct for VHF and UHF bands radiowave transmission.
  - Air index of refraction variations will cause K-factor variations. In general, the normal values of K in VHF and UHF communications are as follows:

    In VHF band, it is similar to standard condition (equal to 1.33).
    In lower UHF band, i.e., less than 1 GHz, K-factor is normally about 1–1.33.
    In upper UHF band, consisting of frequencies between 1 and 3 GHz, K-factor is normally about 1 with 25 % tolerance.

  - Earth magnetic field effects which cause the rotation of radiowaves in elevated layers produced by the ionization of atmosphere molecules. This phenomenon is mostly in HF and lower bands, while its effects on the VHF and UHF are negligible.
  - Galaxy, sky, and sun noises are small in VHF and UHF bands, and specially their values will be reduced when the frequency is increased.
  - Radiowave polarization variations in the VHF and UHF bands and their effects on the wireless communications are presented in Chap. 5.

6.10 Earth Effects

The Earth effects are mostly in suburban mobile communications including the following main factors:

- Mountains and hills
- Forests, woodlands, and vegetation covers
- Oceans, seawater, and rivers
- Flat and coastal areas

The mountain and hill effects on diffraction-based radio communications were explained in Sect. 6.2 while the effects of forests and vegetation covers were discussed in Chap. 3. Seawater and flat area effects are outlined here.

6.10.1 Seawater

The main points about VHF and UHF radiowave propagation above the seawater are as follows:

- The effective height of transmitter and receiver antennas in spite of the mountainous regions is equivalent to their height above the sea level.
- The seawater attenuation index is very big and the penetration depth is very small and negligible.
- At VHF and UHF bands, seawater refraction index is about (-1) and therefore the sea surface is a good reflector for these radiowaves. In some conditions, detected signals in the receiver are summation of direct and reflected waves, and they are stronger than received waves with just the free-space loss.
- The cold and warm water has some different effects on radiowave propagation, and, therefore, recommendation P.1546 provides some different figures for the received signal levels.
- One of the most important effects of seawater in radiowave propagation is the creation of air duct which is more significant in warm zones due to the settlement of water vapors.
- There is no obstacle in radiowave propagation, except at the times when high sea-waves are created due to strong storms. For such situations, the radar horizon and Earth natural bulge should be considered.

6.10.2 Fields and Hills

In flat regions, which are almost without roughness, reflection phenomenon has considerable effects (similar to sea level reflection with index $\Gamma < 1$), because usually there is no bulge in these areas. In spite of the calm sea, the surface of the flat region has a roughness that its relative effects are proportional to radio frequency wavelength. In other words, when the roughness is less than some percentage of wavelength, say less than 10 % of wavelength, the Earth will act as a plane surface; otherwise, it is considered as a rough surface.

For instance, at 100 MHz frequency with wavelength equal to 3 m for roughness less than 30 cm, the Earth will be assumed as a plane surface, while at 2000 MHz frequency it is rough terrain.

When the Earth roughness is considerable, it seems as hills in small scale. The terrain roughness effect which is introduced by Δh may be calculated as shown in Fig. 6.18. In this procedure, 10 % of elevated points and 10 % of deep points are neglected and the average of height variations in some certain distances of this area will be calculated and shown with Δh.

For prediction of the coverage area in the broadcasting systems, ITU has provided two graphs for VHF and UHF bands. According to Figs. 6.19 and 6.20,

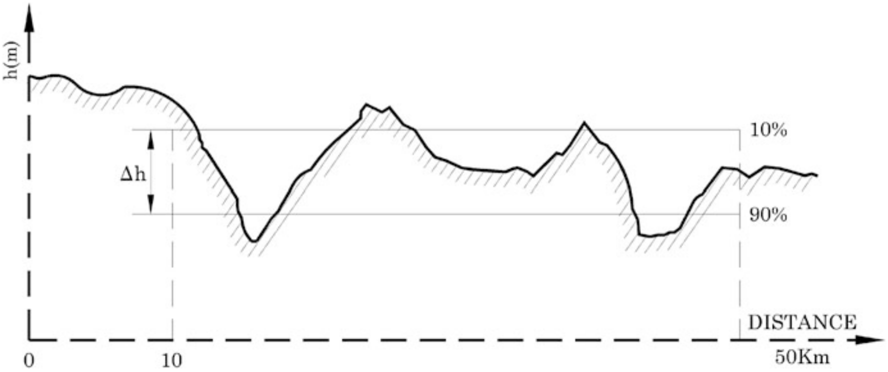


Fig. 6.18 Earth surface roughness concept, Δh

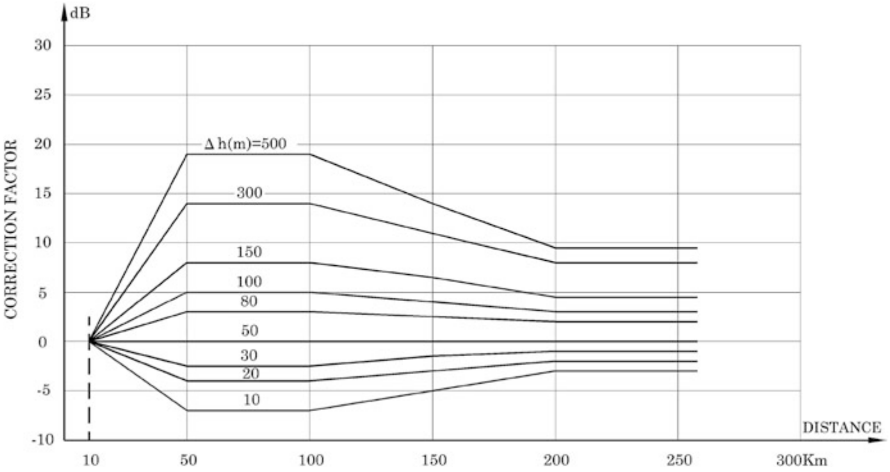


Fig. 6.19 Terrain rolling correction factor, VHF band (Ref.: ITU-R, P.370)

the correction factor can be determined to compensate the path loss based on Δh value. These graphs could be used if there is line-of-sight conditions between the transmitter and receiver.

6.11 Guided Radiowave Propagation

Radiowave transmission while it is confined in a surrounded medium is called the guided radiowave propagation. Some important cases are:

- Tunnels and mines
- Transmission lines like waveguides and RF leaky cables
- Tropospheric ducts

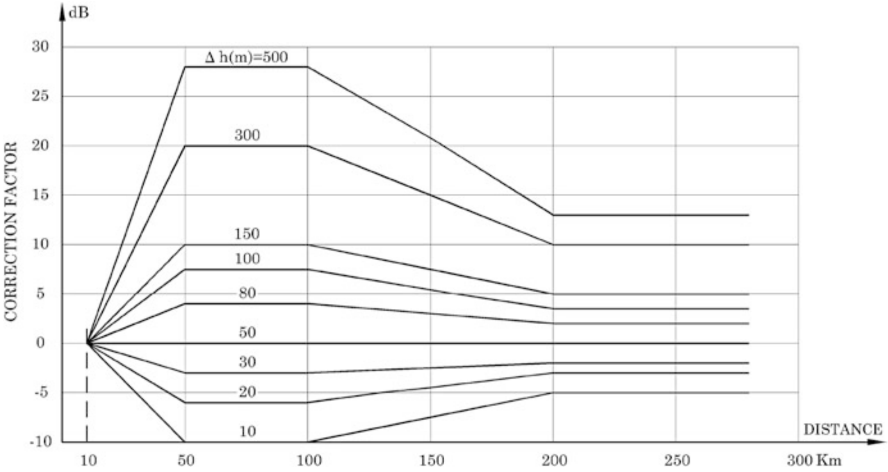


Fig. 6.20 Terrain rolling correction factor, UHF band (Ref.: ITU-R, P.370)

Propagation can be assumed as “guided” whenever a wave front is not free to expand in three dimensions.

6.11.1 Radiowave Propagation in Tunnels

Mobile communications are required in roads and railway tunnels. Also it is necessary to provide reliable communications in mines due to safety and operational issues.

Tunnels with certain lengths and cross-section dimensions are comparable with waveguides and similar concept can be applied for radiowave propagation inside them. Transverse electric (TE) or transverse magnetic (TM) radiowaves may propagate in tunnels. Each propagation mode has a critical frequency, f_c, that radiowaves at frequencies less than f_c can not propagate. The critical frequency is called cut off frequency for which more details and formulas are given for rectangular and circular waveguides in Chap. 9.

In a rectangular waveguide, the cut-off frequency wavelength is twice of its cross-section length; therefore, in a tunnel with 8-m cross-section length, the cut-off wavelength is equal to 16 m, and this value is obtained according to this assumption:

$$f_c = \frac{C}{\lambda} \Rightarrow f_c = \frac{3 \times 10^8}{16} = 18.75\,\text{MHz} \tag{6.65}$$

So all frequencies more than 18.75 MHz with an appropriate mode can propagate in this tunnel.

Because of the tunnel obstacles, which could be mobile or fixed, waves with frequencies more than the cut-off frequency will be diffracted including some diffraction loss. The tunnels loss coefficient has a big range of variations due to the following main factors:

- Rough surface in the tunnel
- Tunnel path direction variations
- Internal permanent or temporary obstacles

At frequencies quite more than the cut-off, propagation within a tunnel can also be interpreted in terms of ray theory, and this is generally more appropriate as the wavelength becomes very small compared to the tunnel cross section. A tunnel with smooth sides compared with wavelength will support propagation by wall reflections at grazing angles. Due to the large variety of reflected paths available, the result has multipath nature with Rayleigh or Rician fading distribution.

Obstructions in a tunnel will cause radiowaves well above the cut-off frequency to be scattered. In general, it will interrupt the process of grazing-incidence reflections and diffraction loss will be experienced immediately beyond an obstruction due to shadowing.

In a road tunnel, loss rate usually changes between 0.1 and 1 dB/m and sometimes there are values out of this range.

6.11.2 Leaky Feeders

Leaky RF feeders are used in tunnels or some other surrounded areas for radiowave propagation to provide mobile communications. More details are given in Chap. 15. They are often used to overcome limitations to propagation within a tunnel or surrounded areas and are the most practical method of supporting required telecommunications services.

Leaky RF feeders usually consist of a foam dielectric heliax cable including slots spacing regularly on its outer conductor. Some electromagnetic energy will leak through the outer conductor as a transverse electromagnetic (TEM)-type wave between the feeder and tunnel walls. This process is referred to as mode conversion.

6.11.3 Air Duct

Another guided radiowave propagation is performed in air ducts as a natural waveguide. Some natural ducts have special dimensions such that in VHF and UHF bands, the wave propagation has a good quality and very low loss. In other words, while waves transmitted in a duct, due to repeated reflections from duct surface, similar to wave transmission in optical fiber, wave can propagate for long distances.

6.12 Mobility Effects

6.12.1 Surrounded Areas

When a mobile set enters a surrounded area like buildings, factories, etc., it will suffer some additional loss to penetrate inside. The ratio of field strengths inside and outside is defined as the building loss (in the logarithmic scale, it is the difference between signal level inside and outside measured in dB). This loss value is dependent on structure type, number of floors, walls, ceiling special covers, and other fixed or portable devices. In addition, the loss value is also dependent on radio channel frequencies.

Industrial buildings typically made up with some metallic structures including some vapors, gases, and particular chemical materials in them produce considerable loss on radiowaves.

Because of extensive application of mobile radio systems, several companies and research groups have conducted researches on the effect of buildings and other structures on radiowave propagation. Some results about the mobile communications in satellite systems are presented in Chap. 4. Also ITU-R recommendation P.1238 contains more details in this respect.

6.12.2 Body Loss

The body effects on radiowaves should be studied since in the mobile communications there are some handset devices such as personal mobile radio units, cell phone, and paging devices which are used very close and sometimes in contact with the human body. When antenna is used near the body, the negative effects of body on radiowaves will be more considerable. On the other hand, radiowaves especially when they are transmitted from a mobile antenna have negative impacts on human body organs particularly on the brain.

The body effects on mobile radiowaves are frequency dependent. As a sample in Fig. 6.21, the body losses are given at different frequencies.

6.13 Media Conditions

6.13.1 Introduction

One of the key factors in fixed radio station coverage estimation, is the radiowave propagation media effects, which are divided into the following parts:

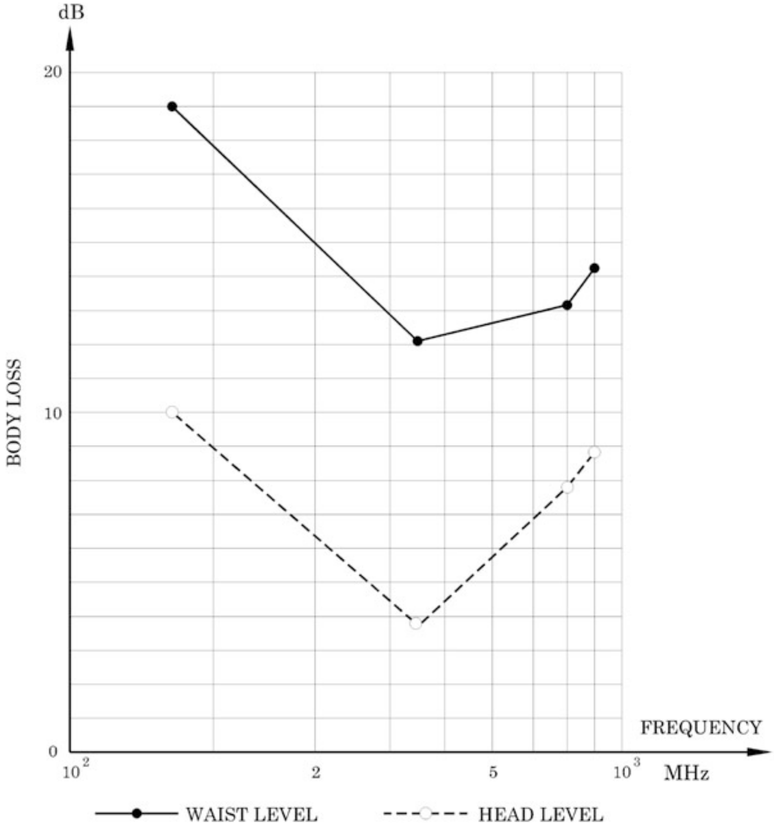


Fig. 6.21 Typical body loss (Ref.: ITU-R, P-1406)

- Natural parameters such as terrain structure along wave paths
- Artificial parameters such as buildings and man-made structures

The obtained results reveal that median received signal level is a function of the mentioned parameters, so classifications and formulation of media effects is very important.

6.13.2 Main Factors

In the professional and accurate studies and calculation models, the following parameters must be considered:

- Natural and man-made noises
- Required coverage area

- Coverage area structure
- Noise frequency and radio interferences
- Radio path-length
- Multipath effects
- Fixed station numbers
- Variation of atmospheric refraction index
- Climate conditions and height
- Formation of atmospheric ducts

The popular classification referenced by some authorities is as follows:

- Open areas consisting of undeveloped regions, mountains, fields, forest areas, and seas.
- Suburban areas including small cities and industrial areas which could consist of residential areas, small industrial regions, and shopping centers with average traffic.
- Urban areas including business centers and big industrial plants, high buildings, and roads and highways with a heavy traffic. This category may further be divided into medium- and large-scale cities.

In practice for detailed design, some additional classes may be considered based on the local terrain conditions and man-made structures. Also, site-specific data supported by local measurements are used to define the related parameters.

6.13.3 Received Power Equation

Considering the mentioned classification in the previous section, the second group which is the suburban areas and small cities could be assumed as an average condition, because the received signal in the open areas is normally better than this average, while the received signal level in urban areas is worse than it. Therefore, a simple equation can be used to calculate the received signal level for the second group, i.e., suburban areas. Received signal level estimation for the first and third types of regions may be performed considering the relative effects.

As shown in Fig. 6.22, the assumed normal conditions for a BTS station are:

- The transmitter power equal to 10 W corresponding to 40 dB_m
- Receiver antenna gain equal to 6 dB_d
- Antenna height equal to 30 m

Some experimental results are as follows:

1. The received power average level has a log-normal distribution with a $\sigma = 8$ dB standard deviation.
2. The received signal power in 1-km distance is equal to $-54\,\mathrm{dB}_m$.
3. The received power over distance slope is equal to 38.4 dB/dec corresponding to 11.55 dB/oct, which is equivalent to 3.84 in linear scale.

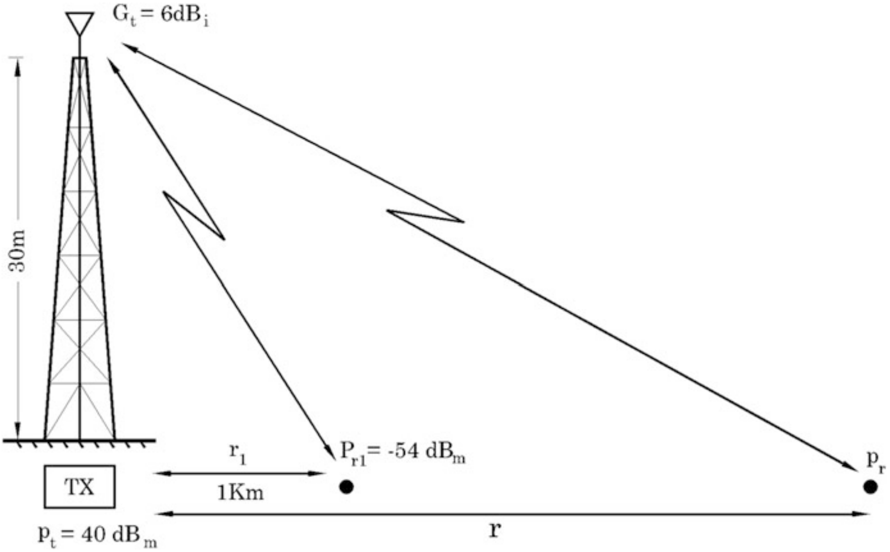


Fig. 6.22 Reference conditions for received power calculation

The received signal power, P_r, at a point with distance of r kilometer from transmitter can be calculated by

$$P_r = P_{r1} \cdot r^{-\gamma} \cdot C_0 \tag{6.66}$$

In this equation, P_{r1} is the signal power at 1-km distance, r indicates the distance in kilometer, and γ is the slope of power reduction over the distance. According to the practical experiments, the correction factor denoted by C_0 is a function of the following parameters:

- Transmitter power
- Antenna height
- Antenna gain

$$C_0 = C_t \cdot C_h \cdot C_g \tag{6.67}$$

$$C_t = \frac{P_t(W)}{10}, \quad C_h = \left(\frac{h_t(m)}{30}\right)^2, \quad C_g = \frac{G(r)}{4} \tag{6.68}$$

Based on the above explanation, the simple equation for the received signal power could be derived as follows:

$$\begin{aligned} P_r\,[\mathrm{dB}_m] = &\ -54 - 38.4\ \log r + 10 \log C_0 \\ = &-54 - \ 38.4\ \log r + 10(\log C_t + \log C_h + \log C_g) \end{aligned} \tag{6.69}$$

It should be noted that the mentioned equation is an approximate equation and more parameters should be considered for the accurate calculation. Also using Eq. (6.68) for the open or urban areas, the appropriate coefficients should be added.

Example 6.11. A 20 W transmitter is radiating radiowaves through an antenna with $g = 6$ at 20 m height; find:

1. Power gain, height gain, and antenna gain
2. Total effects of the above parameters in logarithmic scale

Solution. 1.

$$C_t = \frac{20}{10} = 2, \quad C_h = \left(\frac{20}{30}\right)^2 = \frac{4}{9}$$

$$C_g = \frac{6}{4} = 1.5$$

2.

$$\begin{aligned} 10\log C_0 = {} & 10\left[\log 2 + \log\frac{4}{9} + \log 1.5\right] \\ & = 10\log 4/3 = 1.25\,\text{dB} \end{aligned}$$

■

Example 6.12. A 15 W transmitter radiates radiowaves through 10 dB_i antenna at 20 m height.

1. Find the total gain relative to normal condition in logarithmic system.
2. Assuming 3 dB feeder loss, find the total effect.

Solution. 1.

$$G\,[\text{dB}_d] = G[\text{dB}_i]2.2 \Rightarrow G = 7.8\,\text{dB}_d$$

$$10\log(C_g) = 7.8 - 6 = 1.8\,\text{dB}$$

$$C_t = \frac{15}{10} = 1.5 \quad \Rightarrow \quad 10\log C_t = 1.76$$

$$C_h = \left(\frac{15}{30}\right)^2 = 0.25 \quad \Rightarrow \quad 10\log(C_h) = -6.02$$

2. A 3 dB loss in the feeder reduces the transmitter power (in antenna input) to its half value, so

$$C_t' = \frac{15}{10} \times \frac{1}{2} = 0.75$$

$$C_0 = 10\log C_t' + 10\log C_g + 10\log C_h = -5.47\,\text{dB}$$

■

6.14 Received Signal Level

6.14.1 Introduction

One of the most important factors in the mobile radio system design is calculation of the received signal level in the mobile terminals. In duplex operations (communication), the received signal levels in both sides must be greater than the related receiver threshold level. Two main factors are:

- The minimum received signal level which is dependent on the following two parameters:
  - Sensitivity or receiver threshold value which is specified in two cases, i.e., dynamic and static sensitivity. In mobile communications, the dynamic sensitivity is mostly used except when the mobile terminal operates in a fixed location.
  - Minimum fade margin as a function of standard deviation needed to meet the time and location coverage requirements.
- Connection balance condition:

  In a both-way mobile radio network, uplinks and downlinks are not normally balanced, i.e., the received signal level at both ends is not equal. This is due to using different devices at each terminal for which transmitter power, receiver sensitivity, antenna gain, and diversity techniques are major issues. In an unbalanced mobile radio network, the coverage area for duplex and simplex operations is different.

6.14.2 Link Power Budget Equation

As illustrated in Fig. 6.23, the downlink power budget equation in the BTS to mobile terminal direction in logarithmic scale can be expressed as

$$P_{rM} = P_{tB} - L_c - L_d - L_{fB} - L_p - L_{fM} + G_t + G_r \tag{6.70}$$

In the above equation, the parameters and related units are:

P_{rM}: Received signal power at the mobile terminal in dB$_m$
P_{tB}: BTS transmitter power in dB$_m$
$L_d,\ L_c$: Coupler and duplexer losses in dB
$L_{fB},\ L_{fM}$: Transmitter and terminal feeder losses in dB
L_p: Path loss in terms of dB
$G_t,\ G_r$: BTS transmitter and receiver(terminal) antenna gains in dB$_i$

Also, based on Fig. 6.24, the uplink power budget equation in the mobile terminal toward the BTS direction in logarithmic scale can be expressed with the following equation:

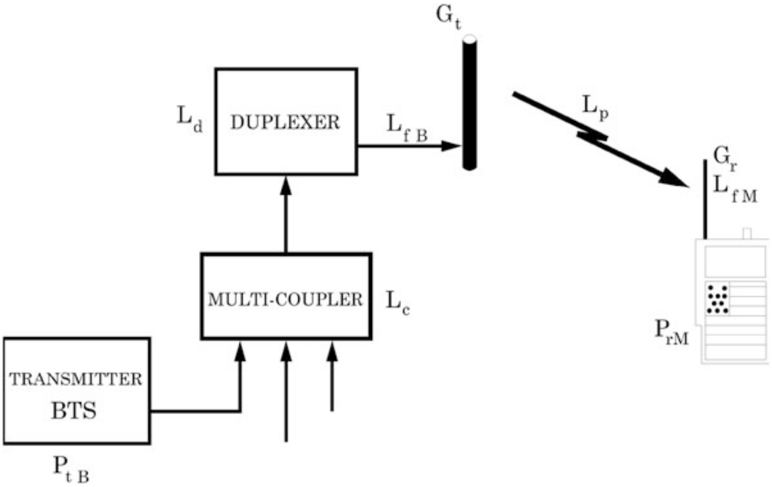


Fig. 6.23 BTS to mobile terminal connection (downlink)

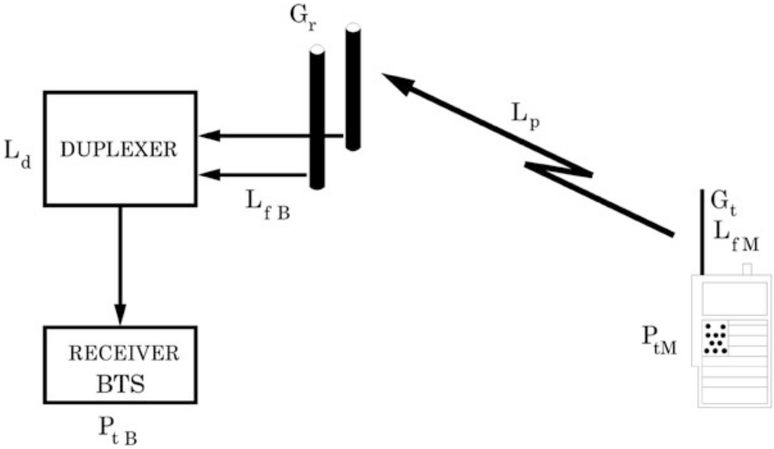


Fig. 6.24 Mobile terminal to BTS connection (uplink)

$$P_{rB} = P_{tM} - L_d - L_p - L_{fM} - L_{fB} + G_t + G_r \tag{6.71}$$

In this equation, P_{rB} is the received signal power in BTS, P_{tM} is terminal transmitter power, and the other parameters are similar to Eq. (6.70). There are some important differences between uplink and downlink equations:

1. There is no coupler loss in uplink.
2. Normally, there is 3–5 dB gain in the uplink receiving system by using antenna space diversity technique in the BTS.

3. BTS receiver sensitivity (receiving threshold) is much better than mobile terminal sensitivity.

The above positive points can compensate the BTS higher transmitter power in downlink.

Example 6.13. Find the BTS transmitter power with the following assumptions:

- Coupler loss: 6 dB
- Duplexer loss: 1 dB
- BTS feeder loss: 6.5 dB
- BTS antenna gain: 12 dB_i
- Path loss: 138 dB
- Pathlength: 15 km
- Receiver sensitivity: −106 dB_m
- Fade margin: 8 dB
- Terminal antenna gain: 2 dB_i
- Terminal feeder loss: 0.5 dB

Solution. According to the receiver sensitivity and required fade margin, the minimum received power is

$$P_{rM} = -106 + 8 = -98\,\mathrm{dB}_m$$

Using Eq. (6.70) and the assumed values

$$P_{tB} = -98 + 6 + 1 + 6.5 - 12 + 138 - 2 + 0.5 = 40\,\mathrm{dB}_m = 10\,\mathrm{W}$$

■

Example 6.14. In the Example 6.13, by using two antennas horizontally spaced in the BTS, 3 dB gain will be provided. Find the BTS received power and fade margin with the following assumptions:

- Mobile TX power: 2 W
- BTS receiver sensitivity: −110 dB_m

Solution.

$$P_{tM}\,[\mathrm{dB}] = 10\log 2\times 10^3 = 33\,\mathrm{dB}_m$$

$$P_{rB} = P_{tM} - L_d - L_p - L_{fM} - L_{fB} + G_t + G_r$$

$$= 33 - 1 - 138 - 0.5 - 6.5 + 12 + 2 = -99\,\mathrm{dB}_m$$

$$P_r = P_{rB} + I_D \quad \Rightarrow \quad P_R = -96\,\mathrm{dB}_m$$

$$\mathrm{FM} = P_r - (-110) \quad \Rightarrow \quad \mathrm{FM} = 14\,\mathrm{dB}$$

■

Example 6.15. In a mobile radio link, the BTS and mobile terminal transmitter power are 25 W and 2 W, respectively. The receiver sensitivities are equal to −110 dB_m and −105 dB_m, and the correction factor of receiver antenna space diversity in the BTS is 3 dB ($L_c = 5$ dB).

1. Is the system balanced or not?

2. Which of the downlink or uplink coverage is greater?

Solution. 1.

$$P_{tB}\,[\mathrm{dB}] = 10\log 25\times 10^3 = 44\,\mathrm{dB}_m$$

$$P_{tM}\,[\mathrm{dB}] = 10\log 2\times 10^3 = 33\,\mathrm{dB}_m$$

The transmitting power gain in downlink is

$$P_{tB} - P_{tM} = 44 - 33 = 11\,\mathrm{dB}_m$$

The receiving gain in uplink is

$$G_D = 3\,\mathrm{dB},\quad G_A = P_{rM} - P_{tB} = -105 + 110 = 5\,\mathrm{dB}_m$$

Considering the results, the total gain on the uplink is

$$G_D + G_A + L_C = 3 + 5 + 5 = 13\,\mathrm{dB}_m$$

So the system is unbalanced and the uplink is in a better condition, so the final coverage is determined based on the downlink (BTS to terminal).

■

6.15 Area Coverage Prediction Models

6.15.1 Introduction

Finding the actual received signal level in the mobile radio receiver is not a simple issue and is dependent on several parameters. The media characteristics also have some effects on radiowave propagation, and therefore distance is not the only factor in the path loss calculation. There are several models to estimate the path loss between the transmitter and the receiver. In addition to the basic models, some experimental models including Okumura–Hata and Lee models are also presented in the next sections:

6.15.2 Classification of Models

The area coverage prediction models in mobile radio systems are based on the following three main categories:

- Empirical model which is based on experimental measurements; the results are dependent on the medium-specific characteristics. Some of these coverage prediction methods employ the Bullington model, Hata model, and Lee model.
- Deterministic model which is based on geometrical structure of building blocks, streets, and some similar cases. The first simple basic model is a sample of this category.
- Physical-statistical model which is based on a combination of deterministic and statistical models of different parameters like building height and road width. The ITU-R, recommendation P.1546 is based on physical equation including some statistical data.

6.15.3 Model Limitations

Each category of prediction models has some limitations as listed below.

- **Empirical Models**
  - Limited frequency range
  - The medium-specific characteristics
  - Lack of physical view on radiowave propagation mechanisms
- **Deterministic Models**
  - Limited application due to mobile communications nature
  - Dedicated to special geometrical structures
  - Electrical characteristics of terrain
  - Requiring different information about path electrical characteristic such as ϵ and σ
  - Complexity due to considering direct, refraction, and diffraction components

6.16 Basic Models

6.16.1 Theoretical Model

This approach is mostly based on deterministic and theoretical expressions including:

- The calculation of free-space loss considered in Chap. 5 and resulting in the following equation for UHF and VHF bands:

$$\text{FSL [dB]} = 32.4 + 20 \log f + 20 \log d \tag{6.72}$$

  In this equation, the distance is in km and frequency is in MHz.

- The path loss in radiowave propagation near the Earth surface which was considered in Chap. 3 and expressed by the following equations:

$$\text{Path Loss} = \frac{P_r}{P_t} = A \cdot \left[\frac{h_b \times h_m}{d^2}\right]^2 \tag{6.73}$$

$$L_p\ [\text{dB}] = 10 \log A - 40 \log d + 20 \log h_b + 20 \log h_m \tag{6.74}$$

In these equations, P_t and P_r are the transmitter and receiver effective powers, h_b and, h_m are the BTS and mobile antenna height in meter, and d is the distance in meter.

6.16.2 Simple Empirical Model

A simple empirical model was introduced in Sect. 6.13 and the relation between the transmitter and receiver power was presented in Eq. (6.66). One of the simple empirical models, which is called clutter factor model, is used for calculation of the path loss in mobile radio networks:

$$\text{Path Loss} = \frac{P_r}{P_t} = \frac{1}{L} = \frac{K}{d^n} \tag{6.75}$$

$$L\ [\text{dB}] = 10n \log d - 10 \log K \tag{6.76}$$

$$L\ [\text{dB}] = 10n \log (d/d_{\text{ref}}) + L_{\text{ref}} \tag{6.77}$$

In the above equations, P_t and P_r are the transmitted and received effective power, respectively, and K and n are the model constants.

In Fig. 6.25, the path loss for plane surface and empirical loss are plotted in terms of clutter factor in logarithmic scale.

To calculate path loss at each geographic point, the model constants will be measured several times and their average will be considered as the reference value. The measurement results show that the path loss is dependent on the fourth power ($n \approx 4$) of distance, for the urban and suburban regions where the following equations are applied:

$$L = \text{plane surface loss} + \text{clutter factor}$$

$$L = 40 \log d + 20 \log f - 20 \log h_b + L_m \tag{6.78}$$

$$L_m = 76.3 - 10 \log h_m, \quad h_m < 10\,\text{m} \tag{6.79}$$

$$L_m = 76.3 - 20 \log h_m, \quad h_m \geq 10\,\text{m} \tag{6.80}$$

In the above equations, the effects of path loss, distance, radio channel frequency, and mobile and fixed antenna heights are considered.

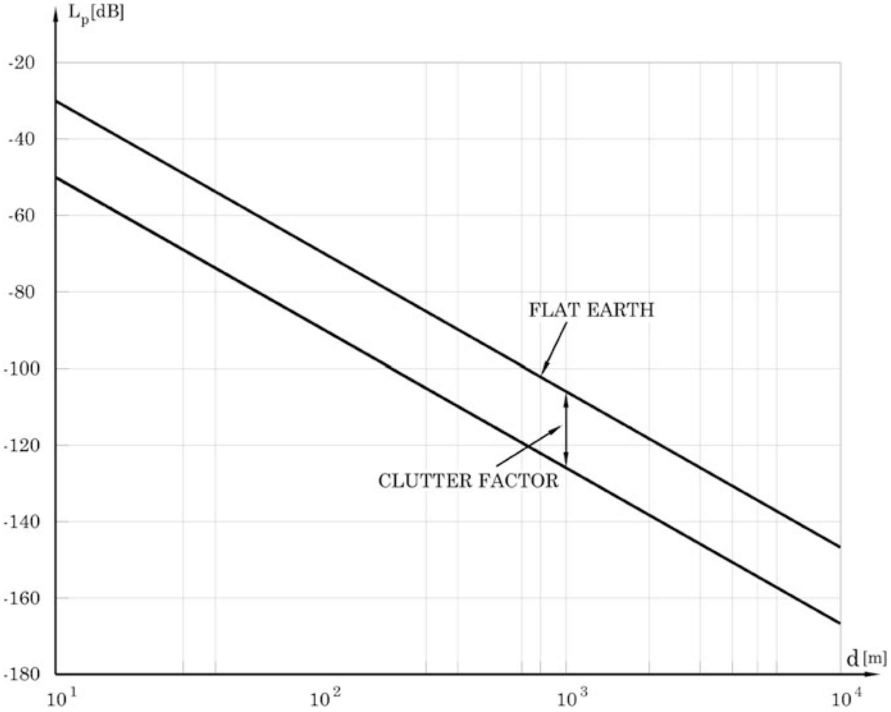


Fig. 6.25 Path loss based on clutter factor

Example 6.16. In a mobile radio network working at 450 MHz and assuming d = 25 km, h_b = 30 m, h_m = 5 m, find path loss using the following methods and compare the results:

1. Free-space loss
2. Wave propagation loss near the Earth (log A = 12 dB)
3. Loss based on clutter factor

Solution. 1. The free-space loss according to Eq. (6.72):

$$\mathrm{FSL} = 32.4 + 20\log 450 + 20\log 25 = 113.4\,\mathrm{dB}$$

2. The path loss in wave propagation near the plane surface according to Eq. (6.74):

$$L_p = 120 + 40\log 25 - 20\log 30 - 20\log 5 = 132.4\,\mathrm{dB}$$

3. The path loss based on the clutter factor model can be calculated by using Eqs. (6.78) and (6.79):

$$L_m = 76.3 - 10\log 5 = 69.3\,\mathrm{dB}$$

$$L = 40\log 25 + 20\log 450 - 20\log 30 + L_m = 148.7\,\text{dB}$$

Comparing the results indicate that $L > L_P >$ FSL and therefore the path loss derived from the applied equation is about 20≈30 dB greater than the theoretical results. ■

6.17 Applied Models

Some important applied models which are used for coverage estimation and calculation in the mobile radio networks are introduced in this section. The main models are:

- Bullington model
- Hata model
- COST 231-Hata model
- Walfisch–Ikaegami model
- Lee model

6.17.1 Bullington Model

This model, as an initial one, is used for VHF band to estimate the received field strength in line-of-sight paths. In the Bullington model, there is no obstacle in radiowave path and the building effects and medium conditions are not considered. This procedure is based on low VHF frequency, low antenna height, vertical polarization, and wet ground. Also, the Earth electrical characteristics shall be considered to determine the antenna effective height.

The first step of received field strength estimation in terms of μV/m is presented in the following equation.

$$E = 88\sqrt{P_t}\,\frac{h_t h_r}{\lambda d^2} \tag{6.81}$$

P_t: Effective radiated power with half-wavelength dipole antenna in W
d: Distance between the transmitter and receiver in km
h_t: Transmitter antenna effective height in m
h_r: Receiver antenna effective height in m
λ: Wavelength in m

The antenna effective height is calculated from the following equations:

$$h_t = \sqrt{{h_1}^2 + {h_0}^2} \tag{6.82}$$

$$h_r = \sqrt{{h_2}^2 + {h_0}^2} \tag{6.83}$$

h_1: Actual height of transmitter antenna in m
h_2: Actual height of receiver antenna in m

And h_0 is derived from the following formula in terms of meter for vertical polarization:

$$h_0 = \frac{\lambda}{2\pi}\left[(\epsilon_r + 1)^2 + (60\lambda\sigma)^2\right]^{1/4} \tag{6.84}$$

For horizontal polarization, the following formula shall be used:

$$h_0 = \frac{\lambda}{2\pi}\left[(\epsilon_r - 1)^2 + (60\lambda\sigma)^2\right]^{-1/4} \tag{6.85}$$

ϵ_r: Earth relative permittivity
σ: Earth conductivity (s/m)

For horizontal polarization at frequencies greater than 40 MHz, the effective antenna height is equal to its actual value.

The Earth electrical characteristics are presented in ITU-R, recommendation P.527. In this method, the following points should be observed:

- For considering the obstruction loss, the equations mentioned in diffraction section may be used.
- To increase the time and location coverage, the required fade margin considering the relevant standard deviations shall be taken into account.
- Terrain roughness is considered as Δh and the relevant correction factors are determined using Figs. 6.19 and 6.20.

Example 6.17. Find the field strength and received power at receiver antenna input using the Bullington method with the following assumptions:

$$P_t = 30\,\text{W},\ \ d = 15\,\text{km},\ \ G_t = 3\,\text{dB}_i,\ \ h_t = 30\,\text{m},\ \ h_r = 4\,\text{m}$$

Solution.

$$G_t = \text{Antilog}\,\frac{3}{10} \quad \Rightarrow \quad G_t = 2$$

$$P_t = G_t \times 30 = 60\,\text{W}$$

$$h_t = 30\,\text{m}, \quad h_r = 4\,\text{m}, \quad \lambda = 2\,\text{m}, \quad d = 15\,\text{km}$$

Using Eq. (6.81), the field strength in the required location is equal to

$$E = 88\sqrt{60} \times \frac{30 \times 4}{2 \times (15)^2} = 181.8\,\mu\text{V/m}$$

For the received power

$$P_r = \frac{1}{2\eta_0} \times E^2 = 43.8\,\text{pW}$$

■

6.17.2 Hata Model

6.17.2.1 Okumura Experiments

Most of the mobile radiowave propagation models in UHF band are based on the experiments and measurements of a Japanese engineer named Okumura. He presented some graphs, typically shown in Fig. 6.26, indicating path loss versus distance based on different conditions including transmitter power, antenna height, and terrain structure and composition.

The Okumura experiments revealed that path loss in mobile radio networks is much greater than the free-space loss in the similar conditions. Thus, the received signal suffers more attenuation.

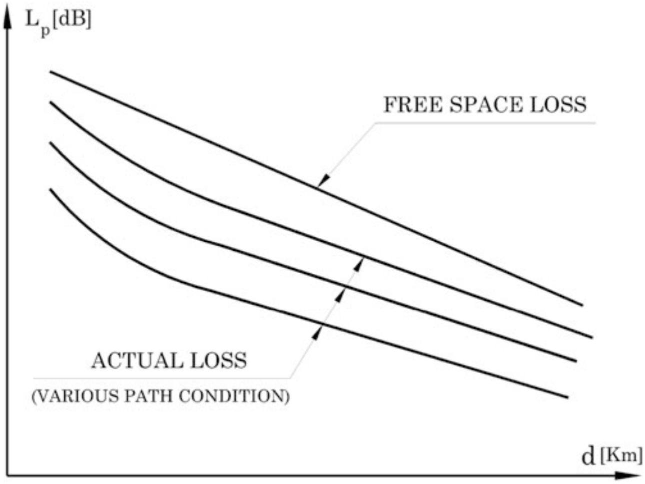


Fig. 6.26 Actual path loss (based on Okumura experiments)

6.17.2.2 Hata Model

Hata model which is used for calculation of mobile radiowave path loss is based on the following conditions. By using this model, area coverage may be predicted for mobile radio networks.

- This model is based on the Okumura experimental results.
- Path loss is presented for different structures.
- This method has the following limitations:
  - Radio channel frequency between 150 and 1500 MHz
  - Path distance between 1 and 20 km
  - Fixed transmitter antenna height between 30 and 200 m
  - Mobile terminal antenna height between 1 and 10 m

Based on the terrain structures along radiowaves path, the Hata model can be classified in the following main categories:

- **Urban Area**
  Built-up city or large town including buildings and houses with two or more storeys or large villages and tall trees, green lands
- **Suburban Area**
  Small town, village or highway scattered with trees and houses, some obstacles near the mobile set but not very congested, and scattered industrial plants
- **Open Area**
  No tall trees or buildings in the radiowaves path, open fields, land cleared for 300–400 m ahead, very low congested area, no factories, farm lands, and rice fields

6.17.2.3 Hata Equations

Hata model equations for calculating the path loss between a fixed transmitter and a mobile receiver in the urban, suburban, and open areas are outlined in the following equations

$$L\,[\mathrm{dB}] = A + B\,\log d - C, \qquad \text{suburban area} \tag{6.86}$$

$$L\,[\mathrm{dB}] = A + B\,\log d - D, \qquad \text{open area} \tag{6.87}$$

$$L\,[\mathrm{dB}] = A + B\,\log d - E_i, \qquad \text{urban area} \tag{6.88}$$

In the above equations, each parameter is expressed by

$$A = 69.55 + 26.16\,\log[f_{\mathrm{MHz}}] - 13.82\,\log h_b \tag{6.89}$$

$$B = 44.9 - 6.55\,\log h_b \tag{6.90}$$

$$C = 2\,[\log(f_{\mathrm{MHz}}/28)]^2 + 5.4 \tag{6.91}$$

$$D = 4.78\,(\log(f_{\mathrm{MHz}}))^2 - 18.33\,\log(f_{\mathrm{MHz}}) + 40.94 \tag{6.92}$$

$$E_1 = 3.2\,(\log(11.75\,h_m))^2 - 4.97 \tag{6.93}$$

$$f_{\mathrm{MHz}} \geq 300\,\mathrm{MHz}, \qquad \text{large cities}$$

$$E_2 = 8.29\,(\log(1.54\,h_m))^2 - 1.1 \tag{6.94}$$

$$f_{\mathrm{MHz}} < 300\,\mathrm{MHz}, \qquad \text{large cities}$$

$$E_3 = (1.1\,\log(f_{\mathrm{MHz}}) - 0.7)h_m - (1.56\,\log(f_{\mathrm{MHz}}) - 0.8), \tag{6.95}$$

$$\text{medium/small cites}$$

Example 6.18. Find radiowave path loss at 420 MHz in 15 km distance for urban, suburban, and open areas. The BTS and mobile antenna heights are 40 m and 5 m, respectively.

Solution. First, the Hata parameters shall be fixed as follows:

$$A = 69.55 + 26.16\,\log(420) - 13.82\log 40 = 116\,\mathrm{dB}$$

$$B = 44.9 - 6.55\log 40 = 34.4\,\mathrm{dB}$$

$$C = 2\left[\log\frac{420}{28}\right]^2 + 5.4 = 8.17\,\mathrm{dB}$$

$$D = 4.78\,[\log(420)]^2 - 18.33\,\log 420 + 40.94 = 25.75\,\mathrm{dB}$$

$$E_1 = 3.2[\log(11.75 \times 5)]^2 - 4.97 = 5.05\,\mathrm{dB}$$

$$E_3 = (1.1\log 420 - 0.7) \times 5 - (1.56\log 420 - 0.8) = 7.6\,\mathrm{dB}$$

The calculated path losses for each category of areas are

$$L_1 = 151.41\,\mathrm{dB} \quad \text{in large cities}$$

$$L_1' = 148.86\,\mathrm{dB} \quad \text{in small cities}$$

$$L_2 = 148.29\,\mathrm{dB} \quad \text{in suburban area}$$

$$L_3 = 130.7\,\mathrm{dB} \quad \text{in open area}$$

■

6.17.3 COST 231-Hata Model

COST is a European entity for scientific and technical researches which extended the application range of the Hata model to cover higher frequencies up to 2000 MHz.

The path loss formula based on this model is

$$L_p = 46.3 + 33.9\log f - 13.82\log h_b + (44.9 - 6.55\log h_b)\log d - E_3 + C_m \tag{6.96}$$

In the above equation, f is in MHz, h_b is in m, d is in km, E_3 is driven from Eq. (6.95), and C_m is as follows:

$$\begin{aligned} C_m &= 3\,\text{dB} \quad \text{in cities} \\ &= 0\,\text{dB} \quad \text{in suburban and medium/small town} \end{aligned}$$

This model is not applicable for micro-cells where the BTS antennas are located in surrounded areas.

Example 6.19. Find the path loss considering the following assumptions, using the Hata and COST-Hata models, and compare the results.

$$f = 1800\,\text{MHz},\ d = 10\,\text{km},\ h_b = 40\,\text{m},\ h_m = 3\,\text{m}$$

Solution. The path loss based on the COST-Hata model:

$$\begin{aligned} E_3 &= (1.1\ \log 1800 - 0.7) \times 3 - (1.56\log 1800 - 0.8) = 4.36\,\text{dB} \\ L_p &= 46.3 + 33.9\log 1800 - 13.82\log 40 \\ &\quad + (44.9 - 6.55\log 40)\log 10 - 4.36 + 3 = 167.56\,\text{dB} \end{aligned}$$

The path loss based on Hata model:

$$\begin{aligned} A &= 132.57\,\text{dB},\ B = 34.4,\ E_3 = 4.36 \\ L &= 132.57 + 34.4\log 10 - 4.36 = 162.61\,\text{dB} \end{aligned}$$

Thus, the actual path loss is about 5 dB greater than Hata model results. ■

6.17.4 Lee Model

Models which were considered so far introduce the path loss equations, but in the Lee model, the relation between the transmitter power and received signal power based on path parameters are presented. This method is based on measurements made in some US cities and is an empirical model.

The Lee equations are based on received power calculation in UHF band and are applicable in public mobile communications networks. These equations are based on Eq. (6.66).

The general form of this equation for the received power, P_r, at distance r from the transmitter is

$$P_r = P_0 - \gamma \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \tag{6.97}$$

The effects of transmitter and receiver antenna heights, transmitter power, and also both antenna gains are considered in α_0 which may be obtained from the following equation:

$$\alpha_0 = 20 \log \left(\frac{h_b}{100} \right) + 10 \log \left(\frac{P_t}{10} \right) + (G_b - 6) + G_m + 10 \log \left(\frac{h_m}{10} \right) \tag{6.98}$$

In the above formula, each component and related unit is

$h_b,\ h_m$: BTS and mobile antenna height in feet
$G_b,\ G_m$: BTS and mobile antenna gains in dB_d
P_t: Transmitter power in W

P_0 and γ as Lee model parameters are based on climate and region-specific values related to buildings, structures, and their heights and can be defined applying local measurement results. The following equations are used for some typical cases:

$$P_r = -49 - 43 \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \quad \text{open area} \tag{6.99}$$

$$P_r = -62 - 38 \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \quad \text{suburban/rural} \tag{6.100}$$

$$P_r = -64 - 43 \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \quad \text{small town} \tag{6.101}$$

$$P_r = -70 - 37 \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \quad \text{medium city} \tag{6.102}$$

$$P_r = -77 - 48 \log r - n \log \left(\frac{f}{900} \right) + \alpha_0 \quad \text{large city} \tag{6.103}$$

Figure 6.27 indicates some typical values of P_0 and γ for different conditions and P_r variations as well.

Also in the above formulas, r is distance between the BTS and mobile terminal in mile and f is radio channel frequency in MHz, while n is a frequency-related parameter with the following values:

$$n = 20, \quad f < 900\,\text{MHz} \tag{6.104}$$

$$n = 30, \quad f > 900\,\text{MHz} \tag{6.105}$$

Example 6.20. 1. Determine the approximate difference between the mobile radiowave power loss in the urban and suburban areas.

2. Find the received power at $f = 450\,\text{MHz}$ and $r = 16.4\,\text{km}$ based on the following assumptions:

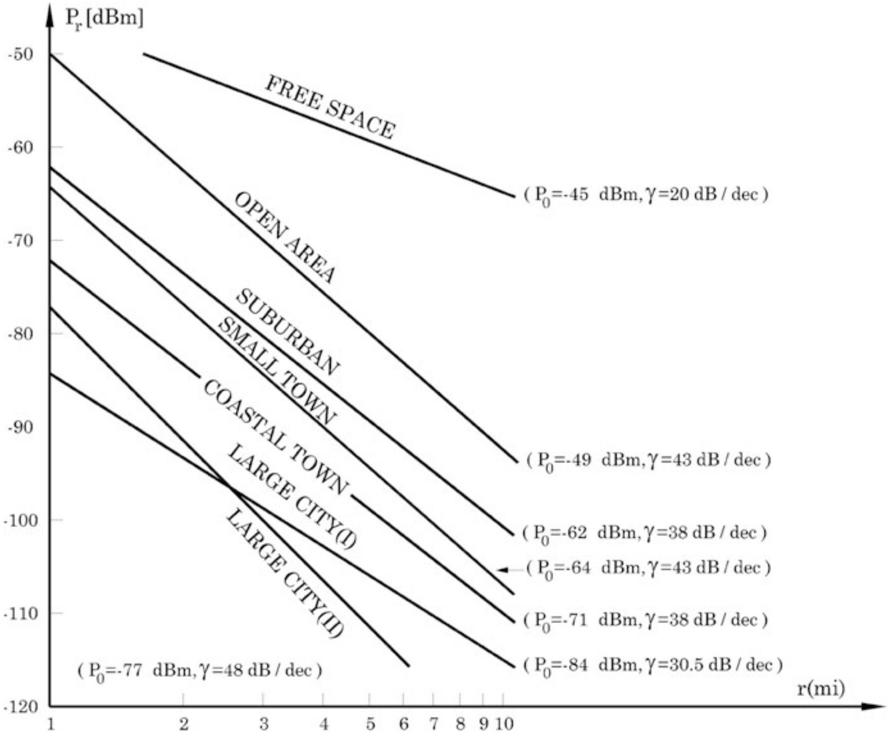


Fig. 6.27 Received power vs. distance (based on Lee model)

$$P_t = 20\,\text{W},\ \ H_b = 30\,\text{m},\ \ h_m = 3\,\text{m},\ \ G_t = 4.2\,\text{dB}_i,\ \ G_r = 0.2\,\text{dB}_i$$

3. Find the path loss.

Solution. 1. The graphs of Fig. 6.27 indicate that the wave path loss difference in the suburban and small towns is a function of distance and in the range of 3–8 dB.

2. Using Eqs. (6.101) and (6.100) and converting the units gives the following result:

$$f = 450\,\text{MHz},\ n = 20,\ r = 10\,\text{mi},\ h_b = 100,\ h_m = 10$$
$$G_t = 14.2 - 2.2 = 12\,\text{dB}_i,\ G_m = -2\,\text{dB}_d$$

In the suburban area, the received signal level is

$$P_r = -62 - 38\log 10 - 20\log\frac{1}{2} + 7 \Rightarrow P_r = -87\,\text{dB}_m$$

In urban area, the received power is

$$P_r = -64 - 43\log 10 - 20\log\frac{1}{2} + 7 \Rightarrow P_r = -94\,\mathrm{dB}_m$$

3. The path loss is equivalent to the ratio of transmitted power to received power in a normal scale or their difference in logarithmic scale, therefore:

$$L_p = P_t\,[\mathrm{dB}_m] - P'_r\,[\mathrm{dB}_m]$$

The received power should be calculated where the transmitter and receiver antenna gain is equal to one, and all the feeder and other connection losses should be neglected. So in this case

$$\begin{aligned}
G'_t &= G'_r = -2.2\,\mathrm{dB}_d\\
\alpha'_0 &= 10\log 2 + (-2.2 - 6) - 2.2 = -7.4\,\mathrm{dB}\\
P'_r &= -62 - 38\log 10 - 20\log\frac{1}{2} - 7.4 = -101.4\,\mathrm{dB}_m, \quad \text{rural area}\\
P'_r &= -64 - 43\log 10 - 20\log\frac{1}{2} - 7.4 = -108.4\,\mathrm{dB}_m \quad \text{in cities}\\
P_t\,[\mathrm{dB}_m] &= 10\log 20\times 10^3 = 43\,\mathrm{dB}_m\\
L_p &= 43 - (-101.4) = 144.4\,\mathrm{dB} \quad \text{in rural area}\\
L_p &= 43 - (-108.4) = 151.4\,\mathrm{dB} \quad \text{in cities}
\end{aligned}$$

■

6.18 Summary

Main propagation issues in terrestrial mobile radio systems were studied, and required explanations, illustrations, formulas, and examples were provided in the present chapter including:

- Major types of mobile radio-communications were introduced and suitable frequency bands indicated.
- Fresnel layers (zones) were defined, its formula derived, and key role of the first Fresnel radius to set suitable criteria for diffraction and line-of-sight conditions were discussed.
- Diffraction phenomenon and related mechanism were studied and basic concepts including penumbra width, diffraction zone, terrain smoothness criterion, isolated obstacles, and types of terrain were specified in accordance with the ITU-R recommendations.
- Diffraction of spherical Earth and obstructions were introduced and studied.

- Knife-edge obstacles as a basic case were defined and related formulas were derived.
- Single, double, and multiple obstacle effects were examined, and suitable procedures for calculation of diffraction loss were presented.
- Propagation medium and its impacts including long/short-term fadings were discussed.
- Signal level fluctuations due to local and temporal variations were taken into account. Major affecting issues such as multipath fading, local ground, terrain structure, mobility, and unbalance links were explained.
- Location and time standard deviations and related expressions based on the ITU-R recommendations were presented to calculate required fade margin for a reliable service in VHF and UHF bands.
- Polarization effects and related diversity techniques for better reception of radiowaves were explained.
- Reflection and multipath phenomena were explained. Time delay spread and its impacts on system performance were studied.
- Earth and climate effects on radiowave propagation considering their structures were studied.
- Radiowave propagation in guided media such as tunnels and mines were studied and RF leaky cables introduced.
- Received power equation and related main factors including system gain, transmitter power, antenna height, and gain were specified.
- Link power budget equation for uplink and downlink was given and major issues introduced.
- Area coverage prediction models classified in empirical, deterministic, and physical-statistical models were explained.
- Basic models for path loss calculation including theoretical clutter factor were discussed.
- Applied models for calculation of received field strength and power such as Bullington, Hata, COST231-Hata, and Lee models were introduced and related expressions and validity ranges determined.

6.19 Exercises

Questions

1. Explain the required conditions to have line-of-sight radiowave propagation in mobile communications.
2. What is the normal values of K-factor in UHF and VHF bands? Are these values dependent on the climate conditions?
3. Explain the first Fresnel radius, its equation, and affecting parameters.
4. Using Fig. 6.3, show that the β_H for all frequencies and the β_V for frequencies lower than 100 MHz are about 1.

5. What is the application of normalized path length and the normalized transmitter and receiver antenna height? Specify their equations.
6. In some references, the following approximate equations are mentioned to calculate the diffraction loss of knife-edge obstacles in terms of the V parameter.

$$\begin{aligned} L_r &= 0 \qquad V < -1 \\ &= 20\log(0.5 - \ 0.62V) \qquad -1 \le V < -1 \\ &= 20\log(0.5 \cdot e^{-0.95V}) \qquad 0 \le V < 1 \\ &= 20\log\left(0.4 - \sqrt{0.1184 - \ (0.38 - \ 0.1V)^2}\right) \qquad 1 \le V < 2.4 \\ &= 20\log\left(\frac{0.0225}{V}\right) \qquad 2.4 \le V \end{aligned}$$

   Show the compatibility of these equations with Eq. (6.21).
7. Explain the location variations in mobile communications and the related affecting parameters.
8. Considering Tables 6.2 and 6.3, specify the variation range of σ_L and σ_t and their relative effects on the total standard deviation.
9. Explain the polarization diversity in mobile communications and its application.
10. Explain the antenna space diversity technique, and its improvement factor and specify the appropriate spacing in the horizontal and vertical situations.
11. What are the main reasons that using the mobile antenna total gain is not possible?
12. Explain the basic situations in considering the multipath fading. What is the Doppler effect and its impacts on radio-communications.
13. Explain the time delay spread in mobile radio-communications.
14. State the effects of the following items on the mobile radio-communications in UHF and VHF bands.

    - Rain and snow
    - Gases and air vapor
    - Atmospheric particles

15. Explain the effective factors emanating from forest trees and vegetation covers loss.
16. Inside tunnels, the FM radiowave in VHF band are detected better than HF or MF radiowaves. (Why?)
17. What is the application of the RF leaky cables?
18. According to Fig. 6.21, investigate the body loss in mobile communications.
19. What are the main media effects on the mobile communications?
20. What is the relation between the received power and distance? State the related correction factors.
21. What is the basic classification of estimation models?

22. Should the transmitter effects and antenna gain be considered in path loss or not?
23. Briefly explain the following calculation procedures for the determination of the path loss in mobile radio systems.
    - Theoretical models
    - Empirical models
    - Applied models
24. What is the main application of Bullington model and, its equation and which parameters are effective in this model?
25. What is the main purpose of Okumura experiments?
26. Explain the Hata model and state its equations and limitations.
27. Explain how the effect of mobile terminal antenna height is considered in Hata model in different conditions.
28. What is the main application of COST 231-Hata?
29. What is the main difference between the Lee model and other models? State the corresponding equations and parameters.
30. Explain the concept of location and time coverage percentage in mobile communications and the applied ranges for frequency band and distance.
31. What is the main purpose of fade margin in mobile radio-communications and which parameters effect it?
32. According to Table 6.1, what are the required fade margin values corresponding to 90, 95, and 98 % location coverage, respectively?

Problems

1. In a radio system operating at $f = 400\,\text{MHz}$, distance of one elevated point on the radio path from both ends is 10 and 15 km; find:

- The first Fresnel radius in the location of elevated point
- Maximum of first Fresnel radius in the whole path
- The Earth bulge in the location of elevated point

2. In a 900 MHz radio link, path distance is about 40 km. Assuming the heights of the transmitter and receiver antennas are 20 m and 10 m, respectively, and $K = 1$, find:

- Normalized admittance of horizontal and vertical polarization for $\epsilon_r = 30$ and $\sigma = 10^{-2}$
- Normalized path length and the corresponding loss
- Transmitter and receiver antenna normalized height
- Path loss

3. In a mobile radio link operating at 400 MHz, the path length is 50 km and $K = 1.33$; find:

- Normalized admittance in horizontal and vertical polarization for $\epsilon_r = 3$ and $\sigma = 10^{-4}$

- Normalized path length

4. The height of a knife-edge obstacle from the connecting line between the transmitter and receiver is 12 m, and the distance between them is 4 and 16 km. Find the obstacle loss for radiowave with $\lambda = 0.5$ m.

5. The height of a knife-edge obstacle from the connecting line between the receiver and transmitter is 30 m with 2 and 5 km distance from the transmitter and receiver. Find the radiowave loss at 900 MHz.

6. An obstacle is located of 8 km length at 1200 m above mean sea level (AMSL) in the middle of a radio path. The transmitter and receiver antenna altitudes are 1080 m/AMSL and 1100 m/AMSL, respectively; find:

- The obstacle height from the connecting line between the transmitter and receiver, if $K = 1.33$
- The first Fresnel radius at $f = 150$ MHz
- The obstacle loss

7. According to Fig. 6.28, in a radio link, the transmitter and receiver antennas have the same height, and there are two obstacles in 1 and 3 km distances away from the transmitter and both 30 m high. If the transmitter and receiver distance is 5 km and working at $f = 450$ MHz, find the diffraction loss with the two following methods and compare the results:

- ITU-R method
- Piquonard method

8. Figure 6.29 shows a 25 km simplified path profile; find the diffraction loss at f_1=150 MHz and f_2= 450 MHz.

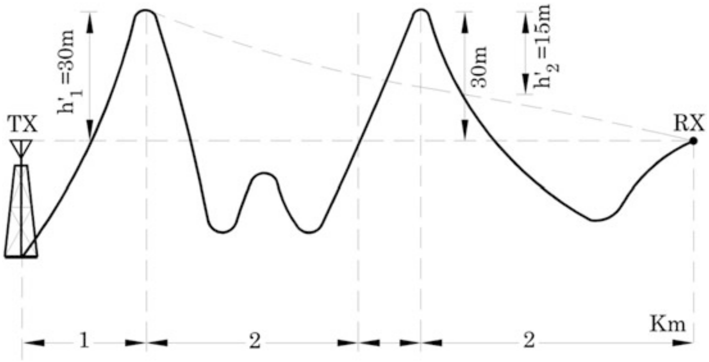


Fig. 6.28 Path profile for Problem 7

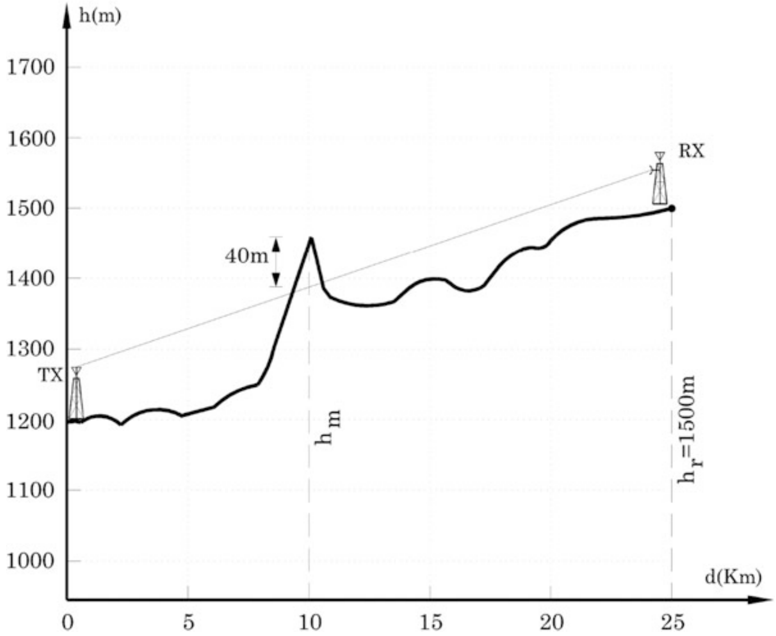


Fig. 6.29 Path profile for Problem 8

9. Find the standard deviation of location variations in a mobile communications link at 170 MHz and the required fade margin for acceptable received signal with a minimum of 95 % of locations. Neglect time variations of the received signal.

10. Determine the standard deviation for location variations in a mobile communications link operating at 162 MHz in a suburban area. Find the ratio of fade margin to the median received signal level for proper receiving in 97 % of locations.

11. Repeat the above problem for σ_t= 2 dB.

12. Repeat Example 6.6 for σ_t= 6 dB and σ_L=8 dB.

13. In a mobile communications link, the BTS antenna height is 20 m.

- If the antenna height increases to 30 and 40 m, respectively, then how much the antenna height gain will increase?
- If the initial received signal level is $-108\,\text{dB}_m$, find the corresponding received signal level in the case of 30-m and 40-m antenna height.
- If the mixed location and time standard deviation is 8 dB, find the coverage improvement corresponding to antenna height increase without the presence of any obstruction in the radio path.

14. The received signal level is $-110\,\text{dB}_m$ in a mobile radio-communications network with a fixed antenna at 30 m height. To increase the received signal level to $-100\,\text{dB}_m$, how much the antenna height should be increased?

15. Find the minimum required distance in space diversity configuration between the BTS antennas at 1800 MHz band for both horizontal and vertical polarizations.

16. BTS antenna of a radio network radiates radiowaves with vertical polarization. If the receiver antenna has a horizontal or circular polarization, what is the difference between the antenna gain in this case and normal conditions?

17. Calculate Doppler frequency at frequency $f = 45$ MHz produced by a vehicular transmitter and detected by a fixed station. Assume 150 km/h speed in a direction of 120° related to radiowave direction.

18. Fig. 6.30 shows a radiowave path profile.

- Find the Δh factor.
- Find the correction factors in UHF and VHF bands for radio broadcasting services to cover up to 100 km.

19. A 20 W transmitter radiates through a $6\,\text{dB}_i$ antenna at 50 m height. By using $3\,\text{dB}_i$ mobile antenna, the received signal power in 2 and 5 km distances are $-80\,\text{dB}_m$ and $-91.6\,\text{dB}_m$, respectively.

- Plot the P_r in terms of distance.
- Find the receiver power in 12 km distance.

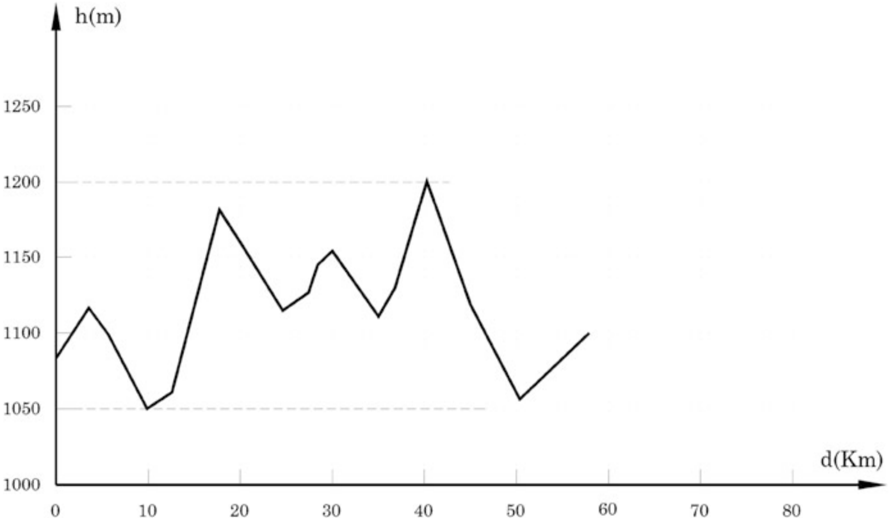


Fig. 6.30 Path profile for Problem 18

- If there is a fixed antenna with 5 dB_i gain at 20-m height in 12 km distance away from the transmitter, find the received signal level.

20. In a mobile radio network operating in UHF band, the BTS transmitter power is 10 W and its receiver sensitivity is $-110\,\mathrm{dB}_m$, while the same parameters for the mobile terminal are 1 W and $-108\,\mathrm{dB}_m$, respectively. Considering the following assumption:

- Coupler loss: 5 dB
- Duplexer loss: 1 dB
- Feeder loss: 4.5 dB
- Path loss: 134 dB
- BTS antenna gain: 12 dB_i
- Terminal antenna gain: $-2\,\mathrm{dB}_i$

Find the fade margin values for uplink and downlink.

21. In the previous problem, by using two antennas spaced properly in the BTS, 3 dB improvement factor is provided. Find the fade margin and new coverage area. Assume 8 km coverage radius for initial conditions.

22. In a mobile radio network, the output power of BTS and mobile transmitters are 20 and 5 W and the sensitivity of receivers are $-114\,\mathrm{dB}_m$ and $-110\,\mathrm{dB}_m$, respectively. The antenna diversity improvement factor is equal to 4 dB:

- Is the system balanced or not?
- Regarding uplink and downlink coverages, which one is greater?

23. Find the radiowave loss using the following methods and assuming $f = 400\,\mathrm{MHz}$, $h_t = 30\,\mathrm{m}$, $h_r = 5\,\mathrm{m}$, and $d = 15\,\mathrm{km}$.

- Free-space loss
- Path loss based on wave propagation near the ground
- Path loss based on clutter factor model

24. A transmitter with 25 W output power is connected to a 6 dB_i antenna with 30-m effective height and, propagates waves at 150 MHz. These waves are received by 2 dB_d antenna with 10 m effective height in 15 km distance. For both cases of horizontal and vertical polarized radiowaves, find:

- Electrical field intensity at receiver location using the Bullington method
- Received signal power
- Path loss

25. A 20 W transmitter connected to 8 dB_i antenna installed at a height of 40 m propagates radiowaves at 800 MHz. A receiver detects them through a 1.5 dB_i antenna located at 4 m high in 8 km remote location. Calculate the received signal level using Hata method for the urban, suburban, and open areas.

26. Repeat the previous problem for receiver antenna height equal to 1, 2, 4, 8, and 10 m and plot the loss variation curve in terms of receiver antenna height in the range of 1–10 m.

27. A remote mobile radio terminal is 25 km away from the related BTS operating at 160 MHz in a suburban area. Find the path loss using Hata method assuming the BTS antenna effective height 100 m and the receiver antenna height 2 m.

28. Find the path loss using the COST-Hata and Lee methods with the following assumptions and compare the results:

$$f = 1800\,\text{MHz},\ h_b = 30\,\text{m},\ h_m = 2\,\text{m},\ d = 10\,\text{km}$$

29. For a remote terminal located at 12 km apart from the BTS and working at 360 MHz, find:

- The received wave power considering the following assumptions:

$$P_t = 10\,\text{W},\ h_b = 36\,\text{m},\ h_m = 2.4\,\text{m},\ G_t = 12\,\text{dB}_i,\ G_r = 0\,\text{dB}_i$$

- The path loss

30. The transmitter power is 20 W and its antenna gain is equal to 6 installed at 20 m height.

- Find the power gain, height gain, and antenna gain.
- How much is the total effect in logarithmic scale?

31. Find the BTS transmitter power if the received signal level in 12 km distance includes 10 dB margin when it is detected by a receiver with $-104\,\text{dB}_m$ sensitivity. Assume the following parameters:

- coupler loss: 6 dB
- Duplexer loss: 1 dB
- BTS feeder loss: 5 dB
- BTS antenna gain: 14 dB_i
- Path loss: 135 dB
- Terminal antenna gain: 2 dB_i
- Terminal feeder loss: 0.5 dB

32. Find the radiowave loss at $f = 600\,\text{MHz}$ for 20 km path length, using the following methods, and compare the results. The height of transmitter and receiver antennas is equal to 37.5 and 5 m:

- Free-space loss
- Path loss based on wave propagation near the flat ground
- Path loss based on clutter factor

33. A 50 W transmitter connected to 2.3 dB_d antenna installed on a tower at 30 m height. Radiated waves are detected by a remote receiver located 20 km from transmitter at 3 m height. Both antennas are adjusted for horizontally polarized radiowaves operating at 150 MHz. Find received signal strength at receiving location.

34. A remote mobile radio terminal located 20 km from the BTS in an urban area operates at 600 MHz. Height of antennas are 75 and 10 m; find:

- The path loss using Hata model.
- Repeat the problem in the case that the path length is reduced to 8 km.
- Repeat the problem, in the case that the distance is reduced to 8 km and BTS antenna height is reduced to 37.5 m.

Chapter 7
Line-of-Sight Propagation

7.1 Introduction

In line-of-sight (LOS) radiocommunications, the main route is the direct path between the transmitter and receiver considering the curvature of radiowave trajectory. In Chap. 2, we discussed the general phenomena such as free-space loss (FSL), gas and vapor loss, Fresnel radius, K-factor, and other mechanisms such as diffraction, reflection, and refraction. In this chapter, we will introduce specific issues related to the line-of-sight wave propagation. These kinds of radiocommunications are mostly employed in the following systems:

- Terrestrial fixed point-to-point communications
- Terrestrial fixed point-to-multipoint communications
- Radar and radio-navigational aids
- Mobile radiocommunications
- Satellite communications
- Fixed point-to-point communications using the passive repeater

This chapter deals with the first two cases, while the remaining subjects are left to the other chapters.

7.1.1 Propagation Environment

Line-of-sight terrestrial wave propagation environment is usually the lower parts of the Earth atmosphere, and the main factors affecting the radiowave propagation are:

A. Ghasemi et al., *Propagation Engineering in Wireless Communications*,
DOI 10.1007/978-3-319-32783-9_7

- Earth atmosphere including its vapors and gases
- Earth topography including terrain structure such as mountains, hills, fields, deserts, and seas
- Natural and man-made factors like forest, tidewater, high buildings/structures, and their long- or short-term changes

The above factors are under influence of the Sun, galaxy, and sky radiations as well as other long- or short-term phenomena on the Earth.

7.1.2 Main Factors

In the LOS radio system design, we will consider the major effects related to the radiowave propagation including the following parameters:

- Diffraction fading where there are one or more obstacles in the radio path
- Propagation conditions and related variations
- Multipath fading and beam spreading called defocusing due to air abnormal refractions
- Fading due to radiowave reflections from the Earth surface or the artificial objects
- Attenuations caused by atmospheric gases and vapors
- Precipitation loss due to rain, snow, hail, and other solid particles in the air
- Variations of the radiowave arrival angle in the receiver antenna or variations of launch angle in the transmitter antenna due to wave refraction in the air
- Decrease of cross-polarization discrimination (XPD), due to multipath or atmospheric precipitation
- Signal distortion due to selective fading and multipath time delay

7.1.3 Frequency Bands

In general, the main frequency bands dedicated to the line-of-sight radiocommunications are UHF, SHF, and EHF bands in frequency range between 300 MHz and 300 GHz. However, at present time because of the increasing demand for radio services, higher-frequency bands such as terahertz and free-space optical (FSO) links are taken into account. For these new frequency bands, reference is made to the selected topics provided in Chap. 8.

According to this wide spectrum, the effects of different phenomena in this kind of communications are different. For example, in frequencies lower than 10 GHz, the effects of precipitation like rain, snow, and fog are negligible, while at frequencies higher than 10 GHz, their effects will be increased and in some cases it could be substantial due to the following reasons:

- Low-communications traffic requirements
- Limitation in the RF component manufacturing technologies

In the early stages, these types of communications were limited to UHF band and part of SHF (lower than 10 GHz). But at the present time, because of the increasing demands for more telecommunications services and achievements in the production of RF components, the LOS radio services on the basis of ITU-R recommendations have expanded to entire SHF and EHF bands as well.

7.2 Ray Trajectory

In the LOS terrestrial communications, radiowaves are not far from the Earth surface level, and actually the troposphere layer and topography of the ground are effective factors.

In Chap. 3, we discussed different concepts about the wave diffraction in the troposphere layer and also K-factor. This chapter is devoted to the line-of-sight radiowave propagation.

7.2.1 Radius of Radio Path Curvature

While radiowaves are passing through a medium, we can consider the following three different cases:

1. When the refraction index is constant, it means that

$$n = cte \quad \Rightarrow \quad dn/dh = 0 \tag{7.1}$$

   In this case, the medium is completely homogeneous and radiowaves will travel along a direct path.
2. When the refraction index has a linear variation versus the height, it means that

$$n = Kh \quad \Rightarrow \quad dn/dh = K = cte \tag{7.2}$$

   In this case, the medium is not homogeneous, but its variation is linear with height (fixed rate variation for n) and radiowaves will follow an arc of a circle.
3. When the refraction index is variable and its variations are not linear, radiowaves will follow a path with variable curvature radius. It means that

$$n = f(h) \quad \Rightarrow \quad dn/dh = f'(h) \neq cte \tag{7.3}$$

In reality the third case will occur which in the short time slots is similar to the second case. Therefore, we can imagine the wave traveling along an arc with varying radii.

Since the atmosphere refraction index is assumed to change with the height, therefore the vertical gradient of refraction index should be considered. In this case the instantaneous radius of path curvature is obtained applying the following equation:

$$\frac{1}{R} = -\frac{n}{\cos \phi} \times \frac{1}{dn/dh} \tag{7.4}$$

In the above equation:

R:	Radius of ray path curvature
n:	Refraction index of the atmosphere
dn/dh:	Vertical gradient of refraction index
h:	Height from the ground level
ϕ:	Angle between the ray path and horizontal line

If the concavity of R is toward the Earth (as shown in Fig. 7.1), then it has a positive sign; otherwise, it has a negative sign. If variation of the atmosphere refraction index during one wavelength was negligible, then it would be independent of frequency, for example, in UHF and higher frequencies.

In line-of-sight terrestrial communications, the wave path is approximately horizontal, so ϕ is almost zero and $\cos \phi$ is equal to one; therefore, Eq. (7.4) can be written as follows that is similar to Eq. (2.76) which was mentioned in Chap. 2.

$$R = -\frac{n}{dn/dh} \tag{7.5}$$

Since the refraction index of air is almost 1, so Eq. (7.5) can be simplified as follows:

$$R = -\frac{1}{dn/dh} \tag{7.6}$$

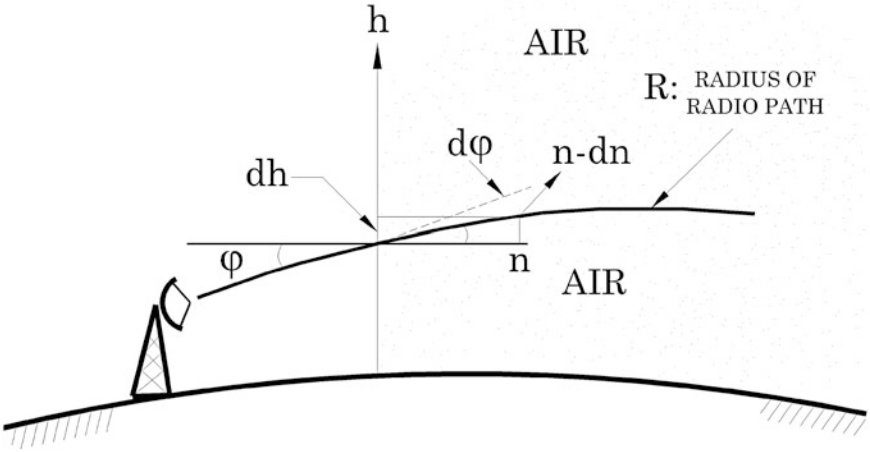


Fig. 7.1 Radiowave trajectory in the troposphere

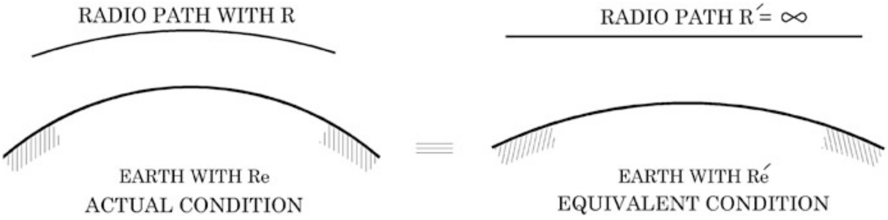


Fig. 7.2 Earth effective radius

In the above equations, it is obvious that if vertical variations and the refraction index are fixed, then R will be a fixed value also, resulting in a circular path for radiowave propagation.

Example 7.1. In line-of-sight communications, distance between the transmitter and receiver is 30 km, and the height above sea level is 200 m, if the vertical gradient of refraction index versus the height is $-40 \times 10^{-6}\ \mathrm{km}^{-1}$. Find the radius of ray path curvature.

Solution.

$$\phi = \arctan\left(\frac{\Delta h}{d}\right) = \arctan\left(\frac{200}{30 \times 10^3}\right) \quad \Rightarrow \quad \phi = 0.38^\circ$$

$$\Rightarrow \quad \cos\phi \approx 1, \quad n \approx 1$$

Using Eq. (7.4) with the above values,

$$\frac{1}{R} = -\frac{1}{-40 \times 10^{-6}} \quad \Rightarrow \quad R = 25{,}000\,\mathrm{km}$$

∎

7.2.2 K-Factor

To simplify the analysis of the LOS radio links, it is convenient to assume the ray path as a straight line. To do so, the relative curvature of ray path in terms of the Earth shall be equally maintained in both cases. The relative curvature in the actual condition is $((1/R_e) - (1/R))$, while it is $((1/R'_e) - (1/R'))$ in the equivalent case; thus, considering Fig. 7.2, we obtain

$$\frac{1}{R_e} - \frac{1}{R} = \frac{1}{R'_e} - \frac{1}{R'} \tag{7.7}$$

where the ray path is assumed a straight line, the value of R' shall be infinity:

$$R' = \infty \quad \Rightarrow \quad \frac{1}{R'_e} = \frac{1}{R_e} + \frac{dn}{dh} \tag{7.8}$$

Based on the definition, the ratio of the Earth effective radius to its actual radius is called K-factor; therefore:

$$K = \frac{R'_e}{R_e} \tag{7.9}$$

$$K = \frac{1}{1 - \frac{R_e}{R}} = \frac{1}{1 + R_e(\frac{dn}{dh})} \tag{7.10}$$

Example 7.2. Refraction index of the atmosphere is expressed by the following equation:

$$n(h) = 1 + a\exp(-bh), \quad a = 0.000315, \quad b = 0.0001361$$

where a and b are the given fixed values and h is height in meters; find:

1. Refraction index at height of 500 m
2. Radius of path curvature for SHF band radiowaves
3. The K-factor

Solution. 1.

$$n(500) = 1.000294$$

$$N(500) = (n - 1) \times 10^6 = 294$$

2.

$$R = \frac{1}{\frac{1}{dn/dh}} \quad \Rightarrow \quad R = \frac{1}{ab\exp(-bh)}$$

$$R = 24{,}968\,\text{km}$$

3.

$$K = \frac{1}{1 - \frac{R_e}{R}} = 1.343$$

■

7.2.3 Earth Atmosphere

To classify different atmosphere conditions, the vertical gradient of refractivity is denoted by N' and is defined as follows:

$$N = (n - 1) \times 10^6 \tag{7.11}$$

$$N' = \frac{dN}{dh} = 10^6 \times \frac{dn}{dh} \tag{7.12}$$

In terrestrial line-of-sight radiocommunications, the Earth atmosphere is classified into the following categories in terms of different values of refractivity vertical gradient, N':

- Subrefractive atmosphere, where $N' > 0$, which means that path cavity is toward the Earth.
- Fixed refractive atmosphere, where $N' = 0$, and

$$K = 1, \quad R = \infty, \quad R'_e = R_e = 6370\,\text{km}$$

- Substandard atmosphere, where $-39 < N' < 0$, so

$$1 < K < 1.33, \quad R > 25{,}000\,\text{km}, \quad R_e < R'_e < 8500\,\text{km}$$

- Standard atmosphere, where $N' = -39$, and

$$K = 1.33, \quad R = 25{,}000\,\text{km}, \quad R'_e = \ 8500\,\text{km}$$

- Above-standard atmosphere, where $-157 \ < N' < -39$, and

$$K > 1.33, \quad R_e < R < 25{,}000\,\text{km}, \quad R'_e > 8500\,\text{km}$$

- Critical atmosphere, where $N' = -157$, so

$$K = \infty, \quad R = R_e, \quad R'_e = \ \infty$$

- Super-refractive atmosphere, where $N' < -157$, so

$$K < 0, \quad R < R_e, \quad R'_e < 0$$

7.2.4 Typical Values of K-Factor

Considering the key role of the K-factor in the analysis of terrestrial LOS radio links and its effects on different calculations, it is important to determine its proper value. More common and typical values for the radio link calculations include the following issues:

- Standard value which is usually equal to $K_s = 4/3 = 1.33$
- Effective value which is shown by K_e and is almost equal to one for long paths. The variation of this factor is given in Fig. 7.3 according to ITU-R recommendations.
- Minimum value denoted as K_m and is based on corresponding troposphere layer parameter measurement.

  In the case where there is no local site-specific information, the following values could be used:

  - Mountainous regions: $K = 0.8$
  - Regions with moderate temperature and altitude: $K = 0.67$
  - Regions with warm climate and moderate altitude: $K = 0.5$
  - Coastal and other special regions: $K < 0.5$

- Maximum value denoted as K_M and usually used in reflection calculations and analysis: $K_M > 2$

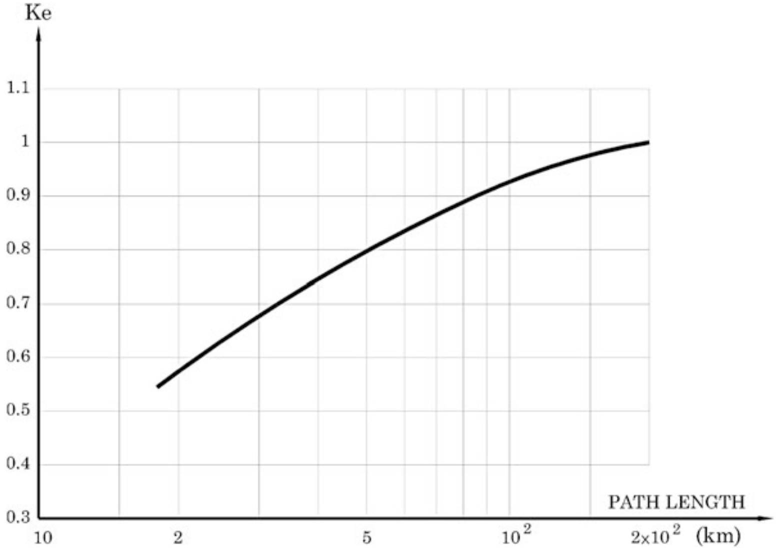


Fig. 7.3 Variation of K_e

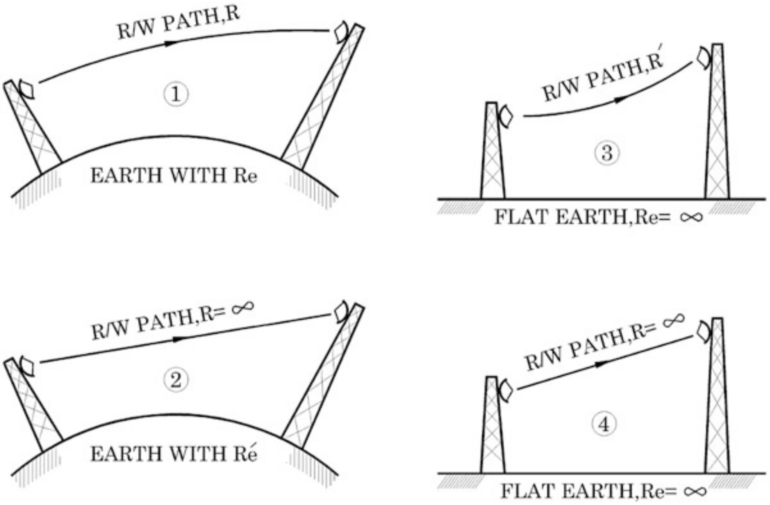


Fig. 7.4 Relative ray path vs. Earth radius

7.2.5 Radio Path Profiles

To study radiowave propagation in the line-of-sight communications and to find the obstruction loss, it is necessary to plot the path profile. For this purpose different methods may be employed to consider terrain structure/heights and atmosphere climatic conditions. As illustrated in Fig. 7.4, the following methods are more common:

1. Actual curvature of the Earth and radiowave path both are assumed to be circles with radii R_e and R, respectively.
2. Straight line ($R' = \infty$) is assumed for radiowave path, while equivalent radius of R'_e is considered for the Earth.
3. The Earth is assumed to be flat and its curvature is embedded into radiowave path which results in the radius of R' for ray path.
4. The Earth is assumed to be flat and radiowave to follow a straight line, but their curvature effects are considered only for critical points.

Normally the first method is not applicable because of its complexity in the analysis of path profiles. For the second method, there are some scaled charts for typical values of K-factor like 1.33, 0.67, and 0.5. As shown in Fig. 7.5, terrain roughness is depicted on the paper based on selected K-factor. Line-of-sight condition is obtained when the straight line connecting two end point (TX and RX) antennas passes over all heights with suitable margin based on the path clearance criteria.

The third method is mostly used in programming and practical applications; one example of this method is shown in Fig. 7.6. In this method considering K-factor and

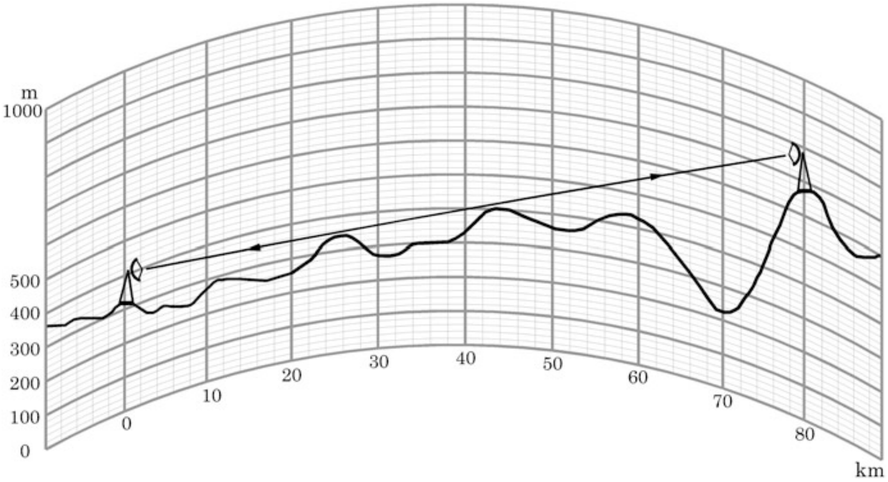


Fig. 7.5 Radio path profile: Earth with effective radius, R'_e

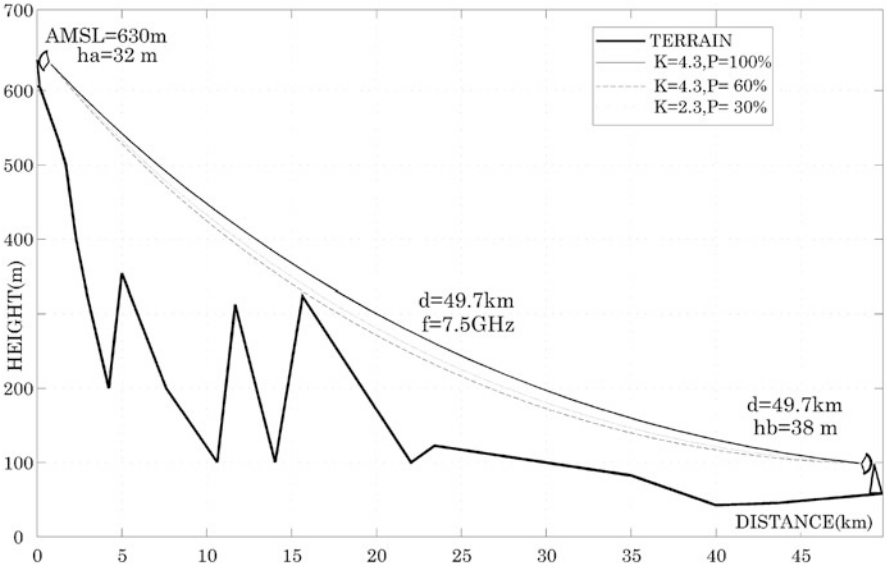


Fig. 7.6 Radio path profile: flat Earth

data regarding to some key points like main and critical points which are obtained from the topography maps of Earth natural structure in the radiowave path, the approximate ray trajectory could be estimated.

It should be noted that in the abovementioned methods, the necessary path clearance (as a portion of the first Fresnel radius) shall be calculated based on the

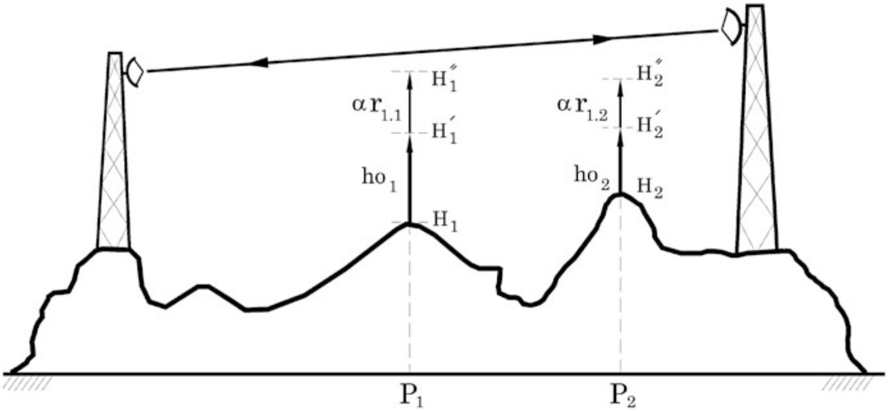


Fig. 7.7 Radio path profile: flat Earth and straight path

selected criteria and be added to the height of each critical point. Then, to obtain LOS condition, the ray path shall pass over all critical heights, with suitable margin.

For the fourth method as illustrated in Fig. 7.7, the following steps shall be done:

- Plot path profile of the natural terrain between two end points.
- Determine the path critical point(s).
- Calculate the Earth bulge for each critical point and selected K-factor and add it on the related height.
- Calculate the path clearance for each critical point and selected K-factor and add it to the related height.

As shown in Fig. 7.7, for LOS condition, the straight line between two end points shall pass over all virtual heights H_1'', H_2'', etc.

Example 7.3. A 30 km radio link is operating at 15 GHz. There are two critical points H_1 and H_2 with above mean sea level (AMSL) of 1200 and 1400 m with distances from transmitter equal to 15 km and 20 km, respectively; find:

1. Radius of the first Fresnel zone and the Earth bulge at H_1 for $K_1 = 1.3$ and path clearance equal to $0.6R_1$ and also the minimum AMSL height of radiowave at H_1.
2. Repeat the case for H_2 assuming $K = 0.7$ and path clearance equal to $0.3R_1$.

Solution. 1. At point H_1 for $K_1 = 1.3$:

$$h_{01} = \frac{500 d_1 d_2}{K_1 R_e} \quad \Rightarrow \quad h_{01} = 13.59\,\text{m}$$

$$\lambda = \frac{C}{f} \quad \Rightarrow \quad \lambda = \frac{3 \times 10^8}{15 \times 10^9} = 0.02\,\text{m}$$

$$r_1 = \sqrt{\frac{d_1 \cdot d_2}{d} \times \lambda} \quad \Rightarrow \quad r_1 = 12.25\,\text{m}$$

$$\alpha_1 = 0.6 \quad \Rightarrow \quad \alpha_1 r_1 = 7.35\,\text{m}$$

$$H_1' = H_1 + h_{01} + \alpha_1 r_1 = 1220.94 \approx 1221\,\text{m}$$

2. At point H_2 for $K_1 = 0.7$:

$$h_{02} = 25.24\,\text{m}$$

$$r_2 = 11.55\,\text{m}, \quad \alpha_2 = 0.3$$

$$H_2' = H_2 + h_{02} + \alpha_2 r_2 = 1400 + 25.24 + 0.3 \times 11.55$$

$$H_2' = 1428.7\,\text{m}$$

Therefore, wave path at points H_1 and H_2 should at least have altitudes of 1221 and 1428.7 m from sea level. ■

7.3 Terrestrial Obstacles

7.3.1 Obstacle Types

In line-of-sight radio links, the obstructions are categorized into the following main groups:

- Permanent obstacles
- Temporary obstacles

Permanent obstacles are those which exist in the radio path between the transmitter (TX) and receiver (RX) antennas due to the terrain structure. To fix the permanent obstacles, local area climatic conditions with normal variations of K-factor and the related clearance criteria shall be taken into account.

Temporary obstructions do not exist in the normal climatic conditions, but they will occur during abnormal cases such as subrefraction where the atmospheric refraction index is less than its regular values. In these cases, K-factor will decrease beyond the normal variation range resulting in higher Earth bulges in the radio path between TX and RX antennas.

Due to low occurrence probability of the abnormal conditions (less than 1 % of time), in order to fulfill propagation availability requirements, a safety factor called fade margin (FM) shall be considered in the LOS radio links. This value may be as high as 40 dB and usually is employed to combat additional losses caused by temporary obstructions. In addition, the fade margin will be used as a countermeasure for other types of fading like multipath or excess losses due to heavy rain or hailstones.

7.3.2 Fresnel Radius

The Fresnel layers, together with their radius and corresponding equations, were discussed in Chap. 3. In each point of the radio path, the first Fresnel radius is obtained from Eq. (3.76) or the following equivalent formula:

$$r_1 = 17.3\sqrt{\frac{d_1 \cdot d_2}{f \cdot d}} \tag{7.13}$$

where:

r_1: First Fresnel radius in m
d_1, d_2: Distance between required point from the transmitter and receiver in km
d: Total radio path length (between the transmitter and the receiver) in km
f: Radio frequency in GHz

7.3.3 Diffraction Loss

While radiowaves encounter the obstacles, some portions of their electromagnetic energy penetrate into the dark region behind the obstacles due to the diffraction mechanism. Diffracted waves will suffer additional losses with magnitudes proportional to type and height of the obstacle and frequency of the RF channel. Diffraction phenomenon and corresponding parameters, equations, and applications were defined in Chaps. 3 and 6 of the book.

Changes of air refraction index will cause variations in the K-factor from its normal value, and therefore the effective radius of Earth, R'_e, will change accordingly as explained in the previous sections. In adverse conditions of atmosphere, the ray path is bent in such a way that the Earth will appear as an obstacle on its route and will cause diffraction loss. This phenomenon is a main factor to fix the antenna height in radio line-of-sight communications.

The diffraction loss depends on the ratio of blocking height to the first Fresnel radius. For a specific path, loss diffraction will be between the upper and lower extremes of knife-edge and rounded obstruction losses. In Fig. 7.8, diffraction loss for UHF/SHF frequency bands is shown (reference frequency is 6.5 GHz).

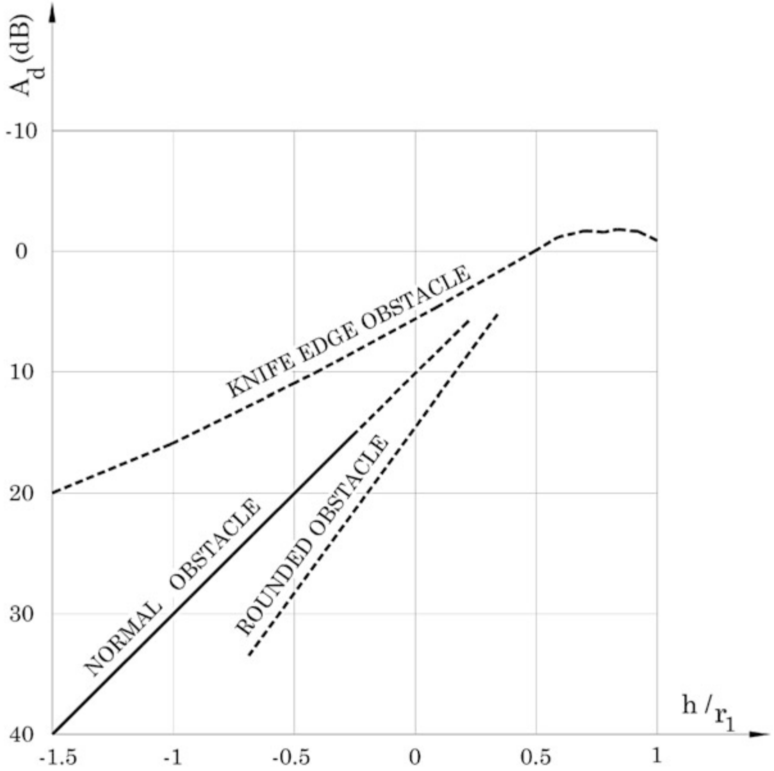


Fig. 7.8 Diffraction loss in LOS radio links (Ref.: ITU-R, P.530)

The diffraction loss over an average terrain can be approximated for losses greater than about 15 dB by the following formula:

$$A_d\,[\text{dB}] = -20\,h/r_1 + 10 \tag{7.14}$$

In this equation the parameters are defined as follows:

A_d: Diffraction loss in dB

h: Obstacle height against the wave path in m (the signs of upper points are negative and lower points are positive)

r_1: First Fresnel radius in meters

Example 7.4. If the obstacle height over the path between the transmitter and receiver is 10 m and the first Fresnel radius at this point is 10 m, find:

1. The obstacle loss and compare the result with Fig. 7.8
2. The loss in the case of knife-edge or rounded obstacle

Solution. 1. Since the obstacle height is higher than the connecting path between the transmitter and receiver, so

$$h/r_1 = -1 \overset{(7.14)}{\Longrightarrow} A_d = +30\,\text{dB}$$

Assuming that $h/r_1 = -1$ and using Fig. 7.8, A_d value is almost +30 dB which is similar to the obtained result.

2. Using Fig. 7.8, for knife-edge and rounded obstacles, we have

$$\text{Knife edge obstacle} \overset{\text{Fig. }7.8}{\Longrightarrow} A'_d \approx 16\,\text{dB}$$

$$\text{Rounded obstacle} \overset{\text{Fig. }7.8}{\Longrightarrow} A'_d \approx 43\,\text{dB}$$

■

7.4 Radio Path Clearance

7.4.1 *Single-Antenna Criterion*

According to the ITU-R P.530 recommendation for the single antenna (where there is no diversity antenna) and assuming the first Fresnel radius r_1, path clearance criterion can be determined through the following steps:

Step 1. Calculate the antenna heights required for the appropriate median value of the local K-factor and 1.0 r_1 clearance over the highest obstacle for both temperate and tropical climates. In the absence of local data, use $k = 1.33$.

Step 2. Obtain the value of K_e from Fig. 7.3 for the path length in question.

Step 3. Calculate the antenna heights required for the value of K_e obtained from step 2 and applying the following criteria:

- **Temperate climate**
  - 0.0 r_1 (i.e., grazing) if there is a single isolated path obstruction
  - 0.3 r_1 if the path obstruction is extended along a portion of the path
- **Tropical climate**
  - 0.6 r_1 for path lengths approximately greater than 30 km

Step 4. Select the larger antenna heights obtained from steps 1 and 3.

In cases of uncertainty as to the type of climate, the more conservative case for tropical climates may be assumed or at least it should be based on an average of the clearances for temperate and tropical climates.

It should be noted that for frequencies less than 2 GHz, smaller fraction of r_1 may be necessary, while for frequencies above 13 GHz, the estimation accuracy of the obstacle height begins to approach 1.0 r_1.

7.4.2 Two-Antenna Space Diversity Criterion

For two antennas used in space diversity configuration, the path clearance may be determined through the following steps:

Step 1. Calculate the height of the upper antenna using the procedure for single-antenna configuration stated in Sect. 7.4.1.

Step 2. Calculate the height of the lower antenna for the appropriate median value of the local K-factor (in the absence of local data, use $K = 1.33$) and the following clearance criterion:

- $0.3r_1$–$0.6r_1$ if the path obstruction is extended along a portion of the path
- $0.0r_1$–$0.3r_1$ if there are one or two isolated obstacles on the path profile

Step 3. Verify that the spacing between the two antennas satisfies the requirements for diversity under multipath fading conditions and, if not, modify accordingly.

It should be noted that the above ranges will give a diffraction loss between 3 and 6 dB and resulting in lower occurrence probability of surface multipath fading. Some paths will not allow the clearance be reduced to this range, and other means must be selected to ameliorate the negative effects of multipath fading.

Also for paths in which surface multipath due to one or more stable surface reflections is a predominant case (e.g., overwater or very flat surface areas), it may be desirable to calculate the height of the upper antenna using the procedure mentioned in Sect. 7.4.1 and then calculate the minimum vertical spacing to avoid surface multipath.

7.4.3 Three-Antenna Space Diversity Configuration

In some extreme situations such as long paths over seawater, it may be necessary to employ three-antenna space diversity. In this case, the following procedure may be taken into account based on the criterion set in Sect. 7.4.2:

1. Place the lowest antenna to meet clearance criterion set in step 2.
2. Place the middle antenna according to the requirement for optimum spacing.
3. Place the upper antenna to ameliorate the effects of surface multipath.

7.4.4 Minimum Antenna Height

The microwave antennas should be placed at an appropriate height from the station ground level. There is no specific standard for the minimum height, while it is recommended to consider the following concerns:

- Existing trees, buildings, and high structures including their future expansions and erection of new ones
- Considering criteria specified in Sect. 7.4.8 for antenna centerline

However, the antenna minimum height is a site-specific issue, but its normal value for a typical repeater is in the range of 5–15 m and for a typical terminal placed in a city or similar location is in the range of 10–25 m above station ground level.

7.4.5 Single-Antenna Height

Single-antenna height is determined based on the method and criteria mentioned in Sect. 7.4.1. If this height is greater than the minimum estimated height, it would be considered, otherwise the minimum height of antenna shall be selected as the final location.

7.4.6 Antenna Space Diversity

Using space diversity of antenna, as depicted in Fig. 7.9 with an appropriate vertical distance from the main antenna, is recommended here in the design of LOS microwave systems. Major reasons to employ antenna space diversity technique in the terrestrial radio links are:

- To reduce adverse effects of multipath fading
- To enhance the improvement factor of radio link by reducing selective fading value
- To act as an antireflective means for radio links over seas

Vertical spacing between the antennas, denoted as V, will be calculated based on its specific application. It should be noted that using antenna space diversity especially in digital microwave systems with adaptive equalizer is a suitable method

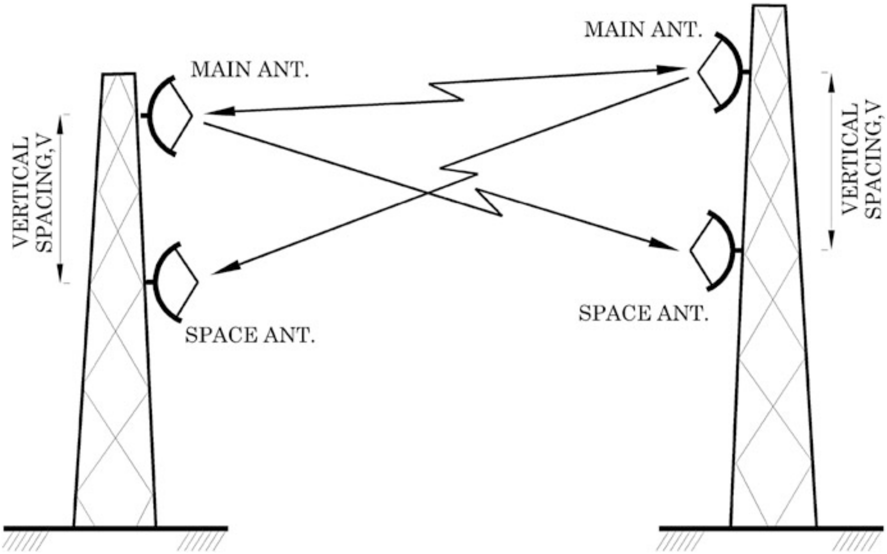


Fig. 7.9 Radio link with antenna space diversity

with synergetic effect to compensate for selective fading. This is a common practice in high and long hops. Selective fading particularly in high-capacity and long hops is more critical, and appropriate countermeasures should be considered. To calculate the main and the space antenna heights, the following method is used:

Step 1. Find the main antenna height using the method provided in Sect. 7.4.1 for single antenna.

Step 2. Calculate the required vertical spacing.

Step 3. Calculating height for the space diversity antenna as per Sect. 7.4.2 will be its final location except where it is less than the minimum antenna centerline as defined in Sect. 7.4.4 for which the latter height will be selected.

Step 4. The main antenna centerline should be placed equal to "*V*" above the space diversity antenna centerline concluded as per step 3.

7.4.7 Optimum Antenna Height

The calculated values for single or double antennas under Sects. 7.4.5 and 7.4.6 are considered as the optimum values. Lower antenna centerlines will cause higher loss resulting in lower fade margin and consequently larger outage probability due to radiowave diffraction. Higher antenna centerline is not recommended and should be avoided because of the following reasons:

- Greater height will cause more reflective paths and also higher fading in some conditions.
- Greater height will result in more feeder loss.
- Greater height will need higher tower increasing the overall cost.

Example 7.5. For a radio link operating at 4 GHz, total path length is 35 km, and the main obstacle with 400 m height from sea level is located 10 km from TX station. End terminal altitudes are 240 and 500 m above mean sea level, and they are located in warm and humid area; find:

1. Earth bulge for $K = 0.5$
2. First Fresnel radius at obstacle point
3. Minimum height for the wave propagating above the obstacle in order to have an appropriate radio link

Solution. 1. Earth bulge is calculated using Eq. (3.28):

$$d_1 = 10\,\text{km}, \quad d_2 = 25\,\text{km}, \quad R_e = 6370\,\text{km}$$

$$h_0 = \frac{500 d_1 \cdot d_2}{K R_e} = 39.25\,\text{m}$$

2. The first Fresnel radius according to Eq. (3.68) is

$$f = 4\,\text{GHz} \quad \Rightarrow \quad \lambda \; = \; 0.075\,\text{m}$$

$$d = 35\,\text{km}, \quad \Rightarrow \quad r_1 = \sqrt{\frac{d_1 d_2 \lambda}{d}} = 23.1\,\text{m}$$

3. Path clearance criteria according to the area climate condition is equal to $0.6\,r_1$, so the wave should pass at least 13.9 m over the obstacle effective height, so the height from the sea level is

$$\text{AMSL} = 400 + 39.2 + 13.9 = 453.1\,\text{m}$$

To meet the above condition, suitable towers with appropriate heights shall be selected. ■

7.4.8 Antenna Around Clearance

In the LOS radio links, high-gain directional antennas are used to provide high-capacity and long-haul communications. For effective operations, observing electromagnetic field properties is a requirement.

As shown in Fig. 7.10a, a round antenna at either end of a radio link is critical. This is due to the near-field effects of antenna having different characteristics from the far field.

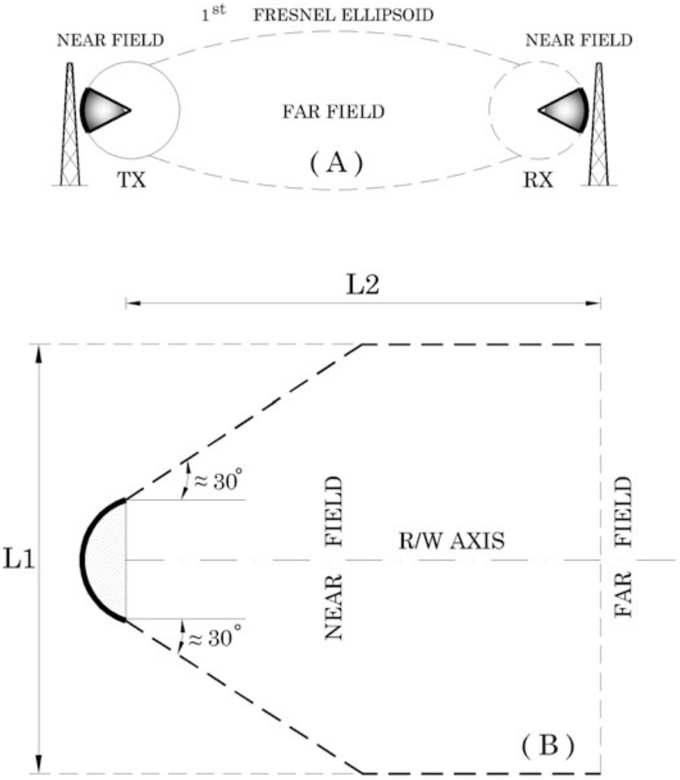


Fig. 7.10 Directional antenna clearance

Near-field distance for a parabolic antenna as mentioned in electromagnetic reference books is defined by the following expression:

$$L_n = D^2/2\lambda = 1.5\,D^2 \cdot f \tag{7.15}$$

where:

L_n: Near-field distance in m
D: Antenna diameter in m
f: Frequency in GHz

For proper operations, near-field clearance should be provided to ensure that all obstructions are in far field with clearance criteria specified in Sect. 7.4.

As shown in Fig. 7.10b for common parabolic antennas used in the terrestrial LOS radio links, vertical (L1) and horizontal (L2) clearance are normally from several meters up to tens of meters depending on antenna diameter and operating frequency.

7.5 Propagation Loss in LOS Radio Links

7.5.1 Communication Equation

In a typical LOS radio link shown in Fig. 7.11, the main parameters are defined as follows:

- Received signal level (RSL) in receiver, in dB_m
- Output power of transmitter (PTX), in dB_m
- Receiver threshold level (minimum acceptable signal power in the receiver) (PRX), in dB_m
- Free-space loss (FSL), in dB
- Waveguide or RF feeder losses related to TX and RX in dB denoted by LFT and LFR, respectively, indicating loss in TX feeder (LFT) and loss in RX feeder (LFR), in dB
- Branching losses in transmitter (LBT) and receiver (LBR), in dB
- Transmitter antenna gain (GT), in dB_i
- Receiver antenna gain (GR), in dB_i
- Miscellaneous losses, LM in dB
- All propagation losses other than free-space loss, L_t, in dB

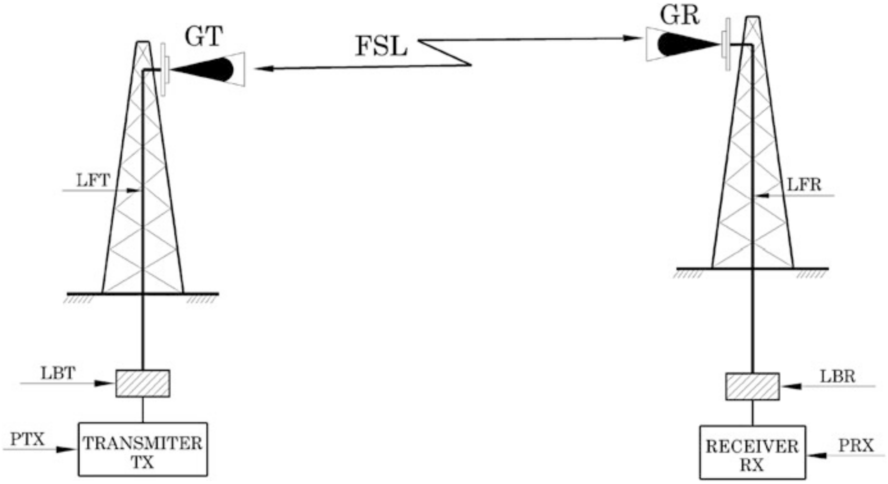


Fig. 7.11 Typical LOS radio link

Considering loss and gain factor in this typical radio link, the received signal level in receiver is obtained from the following equation:

$$\begin{aligned}\text{RSL} = {} & \text{PTX} + \text{GT} + \text{GR} \\ & -(\text{FSL} + \text{LFT} + \text{LFR} + \text{LBT} + \text{LBR} + \text{LM} + L_t)\end{aligned} \tag{7.16}$$

The following points should be taken into account in using Eq. (7.16):

1. Free-space loss is calculated by the following equation:

$$\text{FSL} = 92.4 + 20\log f + 20\log d \tag{7.17}$$

f: Radiowave frequency in terms of GHz
d: Distance between transmitter and receiver in terms of km
FSL: Free-space loss in dB

2. Transmitter effective power denoted as EIRP is obtained from the following equation:

$$\text{EIRP} = \text{PTX} + \text{GT} - \text{LBT} - \text{LFT} \tag{7.18}$$

3. In radio microwave communications, usually the overall merit of transmitter and receiver is called system gain and is defined by the following expression where PRX denotes the receiver threshold level in dB_m.

$$\text{SG} = \text{PTX} - \text{PRX} \tag{7.19}$$

Example 7.6. A LOS radio link with the following characteristics is assumed:

- Radio frequency: 8.4 GHz
- Path distance : 30 km
- Antenna gain: 42 dB_i transmitter and 44 dB_i receiver
- Feeder length: 45 m transmitter and 35 m receiver
- Feeder loss: 6.5 dB per each 100 m
- Transmitter power: 500 mW
- Receiver sensitivity: $-72\ \text{dB}_m$
- Branching loss: 2.6 dB in transmitter and 3 dB in receiver

Find the following parameters: EIRP, SG, FSL, RSL, and FM.

Solution. 1. Effective transmitted power calculation:

$$\text{PTX} = 10\log 500 = 27\ \text{dB}_m, \quad G_T = 42\ \text{dB}_i$$

$$\text{LBT} = 2.6\ \text{dB}, \quad \text{LFT} = 45 \times 6.5/100 = 2.93\ \text{dB}$$

$$\text{EIRP} = 27 + 42 - 2.6 - 2.93 = 63.47\ \text{dB}_m$$

2. System gain calculation:

$$\mathrm{SG} = \mathrm{PTX} - \mathrm{PRX}$$
$$S = 27 - (-72) = 99\,\mathrm{dB}_m$$

3. Free-space loss calculation:

$$\mathrm{FSL} = 92.4 + 20\ \log 8.4 + 20 \log 30 = 140.43\,\mathrm{dB}$$

4. Received signal level calculation:

$$\begin{aligned}\mathrm{PTX} &= 27\,\mathrm{dB}_m, \quad G_t + G_r = 86\,\mathrm{dB}_i\\ \mathrm{LBT} + \mathrm{LBR} &= 5.6\,\mathrm{dB}, \quad \mathrm{LFT} + \mathrm{LFR} = 5.2\,\mathrm{dB}\\ \mathrm{RSL} &= \mathrm{PTX} + G_t + G_r - \mathrm{FSL} - \mathrm{LFT} - \mathrm{LFR} - \mathrm{LBT} - \mathrm{LBR}\\ &= -38.23\,\mathrm{dB}_m\end{aligned}$$

5. Fade margin calculation:

$$\mathrm{FM} = \mathrm{RSL} - \mathrm{PRX} = -38.23 - (-72) = 33.77\,\mathrm{dB}$$

■

7.5.2 Propagation Loss

In line-of-sight radiocommunications, in addition to the free-space loss (FSL), there are some other kinds of losses which are frequency dependent, especially in SHF and EHF frequency bands. Main components of the atmospheric losses related to the radiowave propagation are:

- Precipitation like rain, snow, and hail
- Water vapors and gases
- Fog and cloud
- Sand, dust, and other solid particles in the air
- Permanent and temporary diffraction fading due to total or partial obstruction of the path
- Multipath fading
- Beam spreading and scintillation
- Variations of angle of arrival and angle of launch in radiowaves coupling with antenna

These components are a function of frequency, path length, and geographic location.

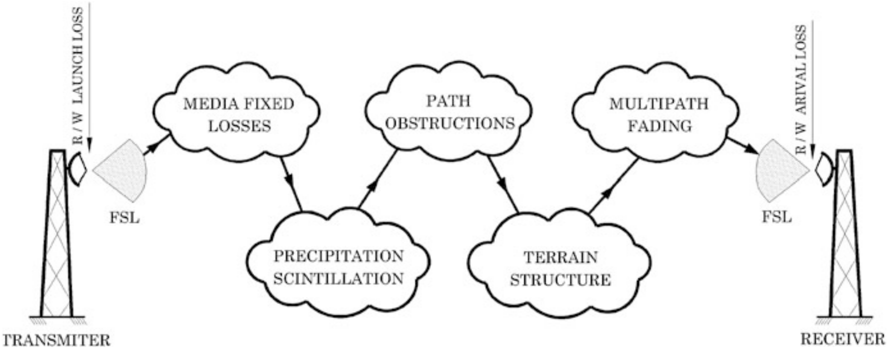


Fig. 7.12 Propagation losses in LOS radio link

In Fig. 7.12, different kinds of losses are shown. In chapter free-space loss and in Chap. 3 rain, fog, and cloud losses were discussed. Also, classical definition of diffraction loss was introduced in Chap. 3, and the practical expressions are given in Chap. 6.

We will deal with the following issues in this section specific to the terrestrial line-of-sight radio links:

- Precipitation loss
- Cross-polarization discrimination, XPD
- Variations of antenna loss related to its coupling to the air

7.5.3 *Precipitation Loss*

7.5.3.1 Introduction

Precipitation like rain, snow, hail, and vapor and gases are all related to the troposphere and discussed in Chap. 3. In the terrestrial line-of-sight radiocommunications, the following points should be considered:

- Since in rainy weather, air near the Earth surface is mixed very well, hence the refraction index will be monotonous and it will be close to the standard condition. In this case, the fading effect due to K-factor will be decreased. Consequently and with the assumption that there is not any reflection path, the main part of the fade margin will combat the rain loss.
- Rain loss can be neglected at frequencies lower than 8 GHz. At frequencies between 8 and 10 GHz, it is significant, and in long-distance paths with frequencies higher than 10 GHz, it should be considered in calculations. Using frequencies higher than 60 GHz and even employment of frequencies above 100 GHz is contemplated in recent years, so the rain loss would be a significant factor.

- According to Fig. 7.14 in Chap. 3 concerning rain, vapor, and oxygen loss in the troposphere layer, the following points should be considered:
  - The rain loss in frequencies higher than 10 GHz
  - Increase of the vapor loss in frequency equal to 22 GHz
  - Increase of the oxygen loss in frequency equal to 60 GHz
- Since the rain loss is considered in design calculation, so in normal situation, the rain cannot result in outage, but severe shower condition which occurs rarely would cause some problems especially in the cases of SHF and EHF bands.

7.5.3.2 Rain Loss Calculation

We will deal with a simplified and step-by-step technique dedicated to the terrestrial line-of-sight radio links. This method is based on the ITU-R P.530 recommendation with some minor modifications. The prediction procedure is considered to be valid in all parts of the world at least for frequencies up to 40 GHz and path lengths up to 60 km.

Step 1. Obtain the rain rate $R_{0.01}$ exceeded for 0.01 % of the time (with an integration time of 1 min). If this information is not available from local sources of long-term measurements, an estimate can be obtained from the information given in the ITU-R P.837 recommendation or in Fig. 7.13.

Step 2. Compute the specific attenuation γ_R (dB/km) for the frequency, polarization, and rain rate of interest using the ITU-R P.838 recommendation or Table 3.3 of Chap. 3 applying the following formula:

$$\gamma_R = K\,R^{\alpha} \tag{7.20}$$

Step 3. Find the effective length in rainy condition, d_e, of the link by multiplying the actual path length d by a distance factor. An estimate of d_e is given by

$$d_e = \frac{d}{1 + d/d_0} \tag{7.21}$$

where, for $R_{0.01} \leq 100$ mm/h,

$$d_0 = 35\, e^{-\,0.015\, R_{0.01}} \tag{7.22}$$

For $R_{0.01} > 100$ mm/h, use the value 100 mm/h in place of $R_{0.01}$.

Step 4. An estimate of the path attenuation exceeded for 0.01 % of the time is given by

$$A_{0.01} = \gamma_R \cdot d_e \quad \text{dB} \tag{7.23}$$

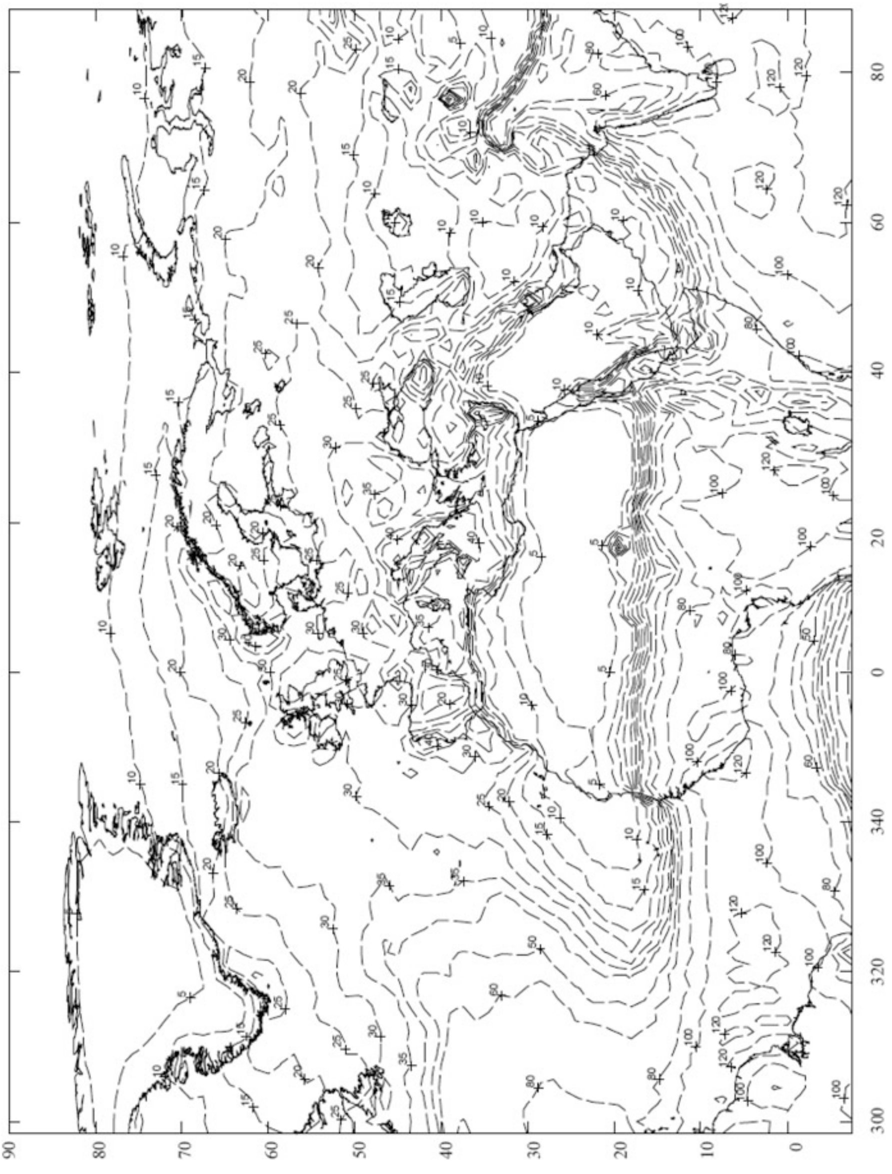


Fig. 7.13 Rain rate (mm/h) exceeded for 0.01 % of the average year (Ref.: ITU-R, P.837)

Step 5. For radio links located in latitudes equal to or greater than 30° (north or south), the attenuation exceeded for other percentages of time p in the range 0.001–1 % may be deduced from the following power law:

$$A_p = 0.12\, A_{0.01} p^{-(0.546+0.043\log_{10} p)} \tag{7.24}$$

This formula has been determined to give factors of 0.12, 0.39, 1, and 2.14 for 1 %, 0.1 %, 0.01 %, and 0.001 %, respectively, and must be used only within this range.

Step 6. For radio links located at latitudes below 30° (north or south), the attenuation exceeded for other percentages of time p in the range 0.001–1 % may be deduced from the following power law:

$$A_p = 0.07 A_{0.01} p^{-(0.855+0.139\log_{10} p)} \tag{7.25}$$

This formula has been determined to give factors of 0.07, 0.36, 1, and 1.44 for 1 %, 0.1 %, 0.01 %, and 0.001 %, respectively, and must be used only within this range.

Step 7. If worst-month statistics are desired, calculate the annual time percentages p corresponding to the worst-month time percentages p_w using climate information specified in the ITU-R P.841 recommendation. The values of A exceeded for percentages of the time p basis will be exceeded for the corresponding percentages of time p_w on worst-month basis

7.5.3.3 Frequency Scaling

When reliable long-term attenuation statistics are available at one frequency, the following empirical expression may be used to obtain a rough estimate of the attenuation statistics at other frequencies in the range of 7–50 GHz, for the same hop length and in the same climatic region:

$$A_2 = A_1\ (\phi_2/\phi_1)^{[1-H]} \tag{7.26}$$

where:

$$\phi(f) = \frac{f^2}{1 + 10^{-4} \times f^2} \tag{7.27}$$

$$H = 1.12 \times 10^{-3} (\phi_2/\phi_1)^{0.5} (\phi_1 A_1)^{0.55} \tag{7.28}$$

A_1 and A_2 are the equiprobable values of the excess rain attenuation at frequencies f_1 and f_2 in GHz, respectively.

7.5.3.4 Polarization Scaling

Given the long-term attenuation statistics at one polarization [either vertical (V) or horizontal (H)], the attenuation for the other polarization over the same link may be estimated using the following formulas:

$$A_V\ [\text{dB}] = \frac{300\, A_H}{335 +\ A_H} \tag{7.29}$$

$$A_H\ [\text{dB}] = \frac{335\, A_V}{300 -\ A_V} \tag{7.30}$$

These expressions are considered to be valid in the range of path length and frequency for this prediction method.

Example 7.7. For a 20 km link working at $f = 15$ GHz and rain intensity $R = 50$ mm/h, find:

1. Effective length and rain loss for radiowaves with horizontal polarization.
2. In the case of changing frequency to $f' = 18$ GHz, find the new rain loss for vertical polarization.

Solution. 1.

$$\begin{aligned} f &= 15\,\text{GHz} \ \Rightarrow\ \alpha_H = 1.154,\ \ K_H = 0.0367 \\ \gamma_R &= K_H \cdot R^{\alpha_H} \ \Rightarrow\ \gamma_R = 3.35\,\text{dB/km} \\ d_0 &= 35\, e^{-0.015\times 50} \ \Rightarrow\ d_0 = 16.5\,\text{km} \\ d_e &= \frac{20}{1+(20/16.5)} = 9.04\ \text{km} \\ A_{0.01} &= \gamma_R \cdot d_e \ \Rightarrow\ A_{0.01} = 30.28\ \text{dB} \end{aligned}$$

2. Using Eqs. (7.27)–(7.29), find rain loss at frequency $f' = 18$ GHz for horizontal polarization, and then using Eq. (7.30), rain loss for vertical polarization at frequency f' will be calculated.

$$\begin{aligned} \Phi(f) &= \frac{15^2}{1+10^{-4}\times 15^2} = 220 \\ \Phi'(f') &= \frac{18^2}{1+10^{-4}\times 18^2} = 313.8 \\ H &= 1.12\times 10^{-3}\cdot (313.8/220)^{0.5} \times (220\times 30.28)^{0.55} = 0.17 \\ A'_H &= A\,(\Phi'/\Phi)^{1-H} \to A'_H = 40.7\,\text{dB} \\ A'_V &= \frac{300\,A'_H}{335+A'_H} \to A'_V = 32.5\,\text{dB} \end{aligned}$$

■

7.5.4 Cross-Polarization Discrimination, XPD

The XPD can deteriorate sufficiently to cause co-channel interference and, to a lesser extent, adjacent channel interference. The reduction in XPD that occurs during both clear-air and precipitation conditions must be taken into account.

7.5.4.1 XPD Outage Due To Clear Air

The combined effect of multipath propagation and the cross-polarization patterns of the antennas governs the reductions in XPD occurring for small percentages of time. To compute the effect of these reductions in link performance, the following step-by-step procedure should be used:

Step 1. Compute

$$\mathrm{XPD}_0 = \begin{cases} \mathrm{XPD}_g + 5 & \text{for } \mathrm{XPD}_g \le 35 \\ 40 & \text{for } \mathrm{XPD}_g > 35 \end{cases} \tag{7.31}$$

where XPD_g is the manufacturer's guaranteed minimum XPD at boresight for both transmitting and receiving antennas, i.e., the minimum transmitting and receiving antenna boresight XPD_s.

Step 2. Evaluate the multipath activity parameter:

$$\eta = 1 - e^{-0.2(P_0)^{0.75}} \tag{7.32}$$

where $P_0 = p_w/100$ is the multipath occurrence factor corresponding to the percentage of the time $p_w(\%)$, exceeding $A = 0$ dB in the average worst month, as calculated from Eq. (7.7) or (7.8), as appropriate.

Step 3. Determine

$$Q = -10\log\left[\frac{k_{\mathrm{XP}} \cdot \eta}{P_0}\right] \tag{7.33}$$

where:

$$k_{\mathrm{XP}} = \begin{cases} 0.7 & \text{one transmit antenna} \\ 1 - 0.3\exp\left[-4\times 10^{-6}\left(\frac{s_t}{\lambda}\right)^2\right] & \text{two transmit antennas} \end{cases} \tag{7.34}$$

In the case where two orthogonally polarized transmissions are from different antennas, the vertical separation is s_t (m) and the carrier wavelength is λ (m).

Step 4. Derive the parameter C from

$$C = \mathrm{XPD}_0 + Q \tag{7.35}$$

Step 5. Calculate the probability of outage P_{XP} due to clear-air cross-polarization from

$$P_{\mathrm{XP}} = P_0 \times 10^{-\frac{M_{\mathrm{XPD}}}{10}} \tag{7.36}$$

where M_{XPD} (dB) is the equivalent XPD margin for a reference bit error rate (BER) given by

$$M_{\mathrm{XPD}} = \begin{cases} C - \frac{C_0}{I} & \text{without XPIC} \\ C - \frac{C_0}{I} + \mathrm{XPIF} & \text{with XPIC} \end{cases} \tag{7.37}$$

Here, C_0/I is the carrier-to-interference ratio for a reference BER, which can be evaluated from either simulation or measurement.

XPIF is a laboratory-measured cross-polarization improvement factor that gives the difference in cross-polarization isolation (XPI) at sufficiently large carrier-to-noise ratio (typically 35 dB) and at a specific BER for systems with and without cross-polarization interference canceller (XPIC). A typical value of XPIF is about 20 dB.

7.5.4.2 XPD Outage Due To Precipitation

Intense rain governs the reductions in XPD observed for small percentages of time. For paths on which more detailed predictions or measurements are not available, a rough estimate of the unconditional distribution of XPD can be obtained from a cumulative distribution of the co-polar attenuation (CPA) for rain using the equiprobability relation:

$$\mathrm{XPD}\ [\mathrm{dB}] = U - V(f) \log \mathrm{CPA} \tag{7.38}$$

The coefficients U and $V(f)$ are in general dependent on a number of variables and empirical parameters, including frequency, f. For line-of-sight paths with small elevation angles and horizontal or vertical polarization, these coefficients may be approximated by

$$U = U_0 + 30\ \log f \tag{7.39}$$

$$V(f) = 12.8 f^{0.19}, \quad \text{for}\ 8 \le f \le 20\,\mathrm{GHz} \tag{7.40}$$

$$V(f) = 22.6, \quad \text{for}\ 20 < f \le 35\,\mathrm{GHz} \tag{7.41}$$

An average value of U_0 of about 15 dB, with a lower bound of 9 dB for all measurements, has been obtained for attenuations greater than 15 dB.

The variability in the values of U and $V(f)$ is such that the difference between the CPA values for vertical and horizontal polarizations is not significant when evaluating XPD. The user is advised to use the value of CPA for circular polarization when working with Eq. (7.38).

Long-term XPD statistics obtained at one frequency can be scaled to another frequency using the semiempirical formula:

$$\mathrm{XPD}_2 = \mathrm{XPD}_1 - 20\log\left(f_2/f_1\right), \quad \text{for } 4 < f_1, f_2 \le 30\,\text{GHz} \tag{7.42}$$

where XPD_1 and XPD_2 are the XPD values not exceeded for the same percentage of time at frequencies f_1 and f_2.

The relationship between XPD and CPA is influenced by many factors, including the residual antenna XPD that has not been taken into account. Equation (7.42) has the least accuracy for large differences between the respective frequencies and the most accuracy if XPD_1 and XPD_2 correspond to the same polarization (horizontal or vertical).

The step-by-step procedure for predicting outage due to precipitation effects are as follows:

Step 1. Determine the path attenuation, $A_{0.01}$ (dB), exceeded for 0.01 % of the time from Eq. (7.23).

Step 2. Determine the equivalent path attenuation, A_p (dB):

$$A_p = 10^{((U - C_0/I + \mathrm{XPIF})/V)} \tag{7.43}$$

Where U is obtained from Eq. (7.39) and V from Eqs. (7.40) and (7.41), C_0/I (dB) is the carrier-to-interference ratio defined for the reference BER without XPIC, and XPIF (dB) is the cross-polarized improvement factor for the reference BER.

If an XPIC device is not used, set XPIF=0.

Step 3. Determine the following parameters:

$$m = \begin{cases} 23.26\log[A_p/0.12A_{0.01}] & \text{if } m \le 40 \\ 40 & \text{otherwise} \end{cases} \tag{7.44}$$

and

$$n = \left(-12.7 + \sqrt{161.23 - 4m}\right)/2 \tag{7.45}$$

Valid values for n must be in the range of −3 to 0. Note that in some cases, especially when an XPIC device is used, values of n less than −3 may be obtained. If this is the case, it should be noted that values of p less than −3 will give outage BER $< 1 \times 10^{-5}$.

Step 4. Determine the outage probability from

$$P_{\mathrm{XPR}} = 10^{(n-2)} \tag{7.46}$$

7.5.5 *Antenna to Air Coupling Loss*

Abnormal gradients of the clear-air refractive index along a path can cause considerable variation in the angles of launch and arrival of the transmitted and received waves. This variation is substantially frequency independent and primarily in the vertical plane of the antennas. The range of angles is greater in humid coastal regions than in dry inland areas. No significant variations have been observed during precipitation conditions.

This effect can be important on long paths in which high-gain/narrow-beam antennas are employed. If the antenna beamwidths are too narrow, the direct outgoing/incoming wave can be sufficiently for off axis that a significant fade can occur. Furthermore, if antennas are aligned during periods of very abnormal angles of arrival, the alignment may not be optimum. Thus, in aligning antennas on critical paths (e.g., long paths in coastal area), it may be desirable to check the alignment several times over a period of a few days.

For example, an antenna with diameter of 3 m and operating at 8 GHz, radiowaves deviated off the axis by 0.875° or 1.5° corresponding to half-power or tenth-power beamwidth will cause 3 dB or 10 dB reduction in the RSL of the receiver or EIRP of the transmitter, respectively.

7.6 Design Criteria

In the design of terrestrial line-of-sight radio networks such as microwave systems, first of all the main criteria including the following issues shall be determined:

- Hypothetical reference circuit
- Grade of system
- Availability/unavailability requirements
- Quality requirements
- Acceptable system performance and outage time

These concepts for terrestrial LOS radio networks are outlined, while more details are provided in other chapters.

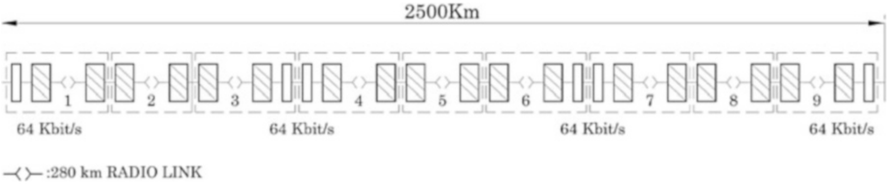


Fig. 7.14 Hypothetical reference digital path (HRDP) (Ref.: ITU-R, F.556)

7.6.1 *Hypothetical Reference Circuit*

Among a variety of hypothetical reference circuits defined by ITU-R, the recommendation no. F.556 is dedicated to the terrestrial hypothetical reference digital path (HRDP). With reference to Fig. 7.14, the total reference length of HRDP is 2500 km which is divided into nine equal sections, each with a 280 km length.

Availability, quality, and performance criteria are defined for the hypothetical reference digital path (HRDP). To indicate the portion related to each real network, guidelines defined by the ITU-R F.634 recommendation must be implemented.

Since calculation of performance, quality and availability parameters, and also failure time of a network is based on the values of these parameters in each hop, so the classification method of unavailability budget, UN performance and nonquality, and failure time between different hops should be considered. The basis of calculation method is in accordance with the ITU-R recommendation F.634 as follows:

- For networks longer than 280 km with linear relation $L/2500$
- For networks with length shorter than 280 km comparing to estimated length of each section (280 km)

7.6.2 *Grade of the System*

In general the terrestrial line-of-sight networks are classified as three main groups according to their system performance requirements.

- High grade (class 1)
- Medium grade (class 2)
- Low grade (class 3)

7.6.3 Availability and Unavailability Criteria

Availability criterion of a digital radio system under operation is defined as the total time for which the bit error rate (BER) is less than one bit in each one thousand received bits, and it means that

$$\mathrm{BER} < 10^{-3} = 10\mathrm{E}(-3) \tag{7.47}$$

Based on this definition, errors which occur in less than ten consecutive seconds are not taken into account for availability, but they are considered for the system quality and performance.

Availability criterion of radio networks based on the ITU-R F.557 recommendation should be between 99.5 and 99.9 % for 2500 km-long hypothetical reference digital path (HRDP). Lower limit of availability range, i.e., around 99.5 %, is normally dedicated to the low-grade networks such as spur links. Average value of around 99.7 % is employed for medium-grade networks such as local or national public networks, and upper limit of around 99.9 % is used for high-grade international or some industry-specific networks. Availability criterion of each radio network is denoted as A, and its reasonable range based on ITU-R definition is

$$99.5\,\% \le A \le 99.9\,\% \tag{7.48}$$

Sometimes instead of percentage, the availability is expressed by a coefficient as follows:

$$a = A/100 \tag{7.49}$$

Similarly, unavailability coefficient is shown by u:

$$u = 1 - a \tag{7.50}$$

and

$$U = (1 - a) \times 100 = 100 - A \tag{7.51}$$

Since the mentioned criteria are for reference network, to calculate unavailability for real networks with a length of L in km and its flat distribution over the network, the following equations can be used:

$$u_a = (1 - a) \cdot L/2500 \tag{7.52}$$

$$U_a = 100(1 - a) \cdot L/2500 \tag{7.53}$$

Due to a variety of failure sources in a radio network, all of the unavailability budget cannot be allocated only to the propagation adverse effects. Some of failure sources include existing power, radio equipment, feeders, antennas, etc. Apportionment of the unavailability budget between the major affecting items highly depends on the network and related operator conditions such as:

- Geoclimatic factors
- Reliability of main electric power
- Available maintenance facilities
- Equipment MTBF and MTTR figures
- HVAC equipment availability
- RF feeder and antenna proper operations

Thus, a suitable apportionment basis for various items shall be decided by experienced engineers. As an example, a rough apportionment of unavailability budget which may be useful for some networks is:

- 30 % for adverse effects of radiowave propagation
- 25 % for radio and electronic equipment
- 25 % for electric power systems
- 20 % for remaining items

Example 7.8. Availability of a 1250 km radio network is 99.8 %. If 30 % of unavailability budget is due to radiowave propagation, find the maximum daily bit error for a system with 155 Mb/s capacity over intervals of ten consecutive seconds or longer per each time.

Solution.

$$A = 99.8\,\% \quad \Rightarrow \quad U = 0.2\,\%$$

$$u = 0.002 \quad \Rightarrow \quad u_e = 0.002 \times \frac{1250}{2500} = 0.001$$

The propagation unavailability value is

$$u_{ep} = 0.001 \times 0.3 = 0.0003 = 3 \times 10^{-4}$$

Total measurement time is $T = 24 \times 60 \times 60 = 86{,}400$ s and system capacity C is

$$C = 155 \times 10^6 \text{ b/s}$$

Therefore, the number of errored bits due to propagation is

$$\begin{aligned} M_{\mathrm{BER} \geq 10\mathrm{E}(-3)} &= C \times u_{\mathrm{ep}} \times T \times 10^{-3} \\ &= 155 \times 10^6 \times 3 \times 10^{-4} \times 86400 \times 10^{-3} \\ &= 4{,}017{,}600 \text{ bits per day} \end{aligned}$$

■

7.6.4 Quality Criterion

Quality criterion in digital communications is related to the following main cases:

- Quality of voice signals should meet the following condition:

$$\mathrm{BER} < 10^{-6} = 10\,\mathrm{E}(-6) \tag{7.54}$$

- Quality of data signals should meet the following condition:

$$\mathrm{BER} < 10^{-8} = 10\,\mathrm{E}(-8) \tag{7.55}$$

Usually quality of digital systems is based on degraded minutes.

Actual radio networks differ in both length and composition from the HRDP, and it is desirable to determine planning objectives of such links, particularly those which are shorter than 2500 km. Thus, finding a reasonable error apportionment in digital radio networks to meet the HRDP requirements is important. Considering that the HRDP comprises nine radio sections, each with a length of 280 km, the following objectives may be adopted for the real links of length L in km:

- For L less than 280 km, the BER should not equal or exceed 10E(−6) during more than (280/2500)×0.4 % of any month with integration time being 1 min, i.e., BER≥ 10E(−6) is acceptable only for a maximum of 0.045 % of any month.
- When $280 \le \mathrm{L} \le 2500$, the BER should not equal or exceed 10E(−6) during a time of more than (L/2500) × 0.4 % of any month with an integration time of 1 min.

In addition to the above criteria, the following factors are also considered for digital signal quality:

- Bit error rate in good condition, in other words residual bit error rate, RBER, which is better than 10E(−10)
- Severely errored second ratio (SESR), in which the bit error rate of them is greater than 10E(−3)
- Errored second ratio (ESR) in which the bit error rate of them is equal to one bit or more

7.6.5 Performance Criterion

Performance criterion is one of the most important parameters in the terrestrial radio network design which may be defined in different ways. For example, in basic digital systems, the following criteria may be adopted:

- In the worst month, bit error rate (BER) for hypothetical reference path with integration time being 1 min should meet the following condition:

$$10\mathrm{E}(-6)\mathrm{BER} < 10\mathrm{E}(-3), \quad \mathrm{DMR} \le 0.4\,\% \tag{7.56}$$

- In the worst month, severely errored seconds for hypothetical reference path with integration time being 1 s should meet the following condition:

$$\text{BER} > 10\text{E}(-3), \quad \text{SESR} \leq 0.054\,\% \tag{7.57}$$

In actual networks, to calculate each of the above criteria, we should use the method mentioned in Sect. 7.6.1. According to the recent improvements in digital equipment, the performance criterion is improved. In current situation, the latest version of ITU-R F.594, F.634, F.696, and F.647 recommendations and ITU-T G.821 and G.826 recommendations is used.

Example 7.9. If the network stated in the previous example is to be competent to operate as part of an international high-grade network, find:

1. Maximum degraded minutes per day when the received signals are unqualified based on BER > 10E(−6)
2. Severely errored seconds (SES) per day

Solution. 1. Based on the defined performance criterion,

$$\text{DM} = 0.004 \times 24 \times 60 \times \frac{1250}{2500} = 2.88 \approx 3\,\text{min}$$

2. Accordingly for SES,

$$\text{SES} = 0.00054 \times 24 \times 60 \times 60 \times \frac{1250}{2500} = 23.3 \approx 24\,\text{s}$$

■

7.7 Fading of the Received Signal

In propagation, radiowaves suffer a variety of attenuations which may be divided into permanent and occasional types.

7.7.1 Permanent Attenuations

Permanent attenuations refer to all continuous, semicontinuous, or short but frequent events. The following items are some of the main permanent attenuations in the LOS radio links:

- Free-space loss
- Normal precipitation losses including rain and snow according to the local statistics

- RF component losses such as feeders, couplers, connectors, circulator, branching circuits, etc.
- Obstruction losses
- Atmospheric aerosol like fog, mist, dust, etc.

Each permanent attenuation shall be considered separately, and its effects should be taken into account in the link budget calculation. However, there are some attenuations with a high potential and permanent nature such as unwanted interfering and overreach signals which are not included here but shall be tolerated by proper engineering and using suitable countermeasures.

7.7.2 Occasional Attenuations

In radiowave propagation, there are some cases which the main signal is attenuated by some phenomena, mechanisms, and events for a short period of time. Major sources of occasional attenuations are:

- Change of reflection point due to atmosphere variations
- Multipath reception
- Natural events like sea tide
- Temporary artificial structures blocking the radio path
- Variations of atmosphere refraction index and radio duct formation
- Precipitation due to abnormal and severe rain, snow, and hail
- Temporary obstruction due to increased Earth bulge which block the radio path partially or totally
- Overreach effects
- Changes in antenna angle of arrival/launch

7.7.3 Fading

Total losses based on the occasional events are called fading and normally are compensated by a safety factor named fade margin (FM). The fade margin is not a fixed value but it depends on a number of factors such as type of radio link, frequency band, propagation reliability requirements, etc. As an example, 20–40 dB is the common range of fade margin in the terrestrial LOS radio links.

Normal occasional attenuations are tolerated by the fade margin, but when its magnitude is more than a predetermined value, it is called deep fading which will result in total outage.

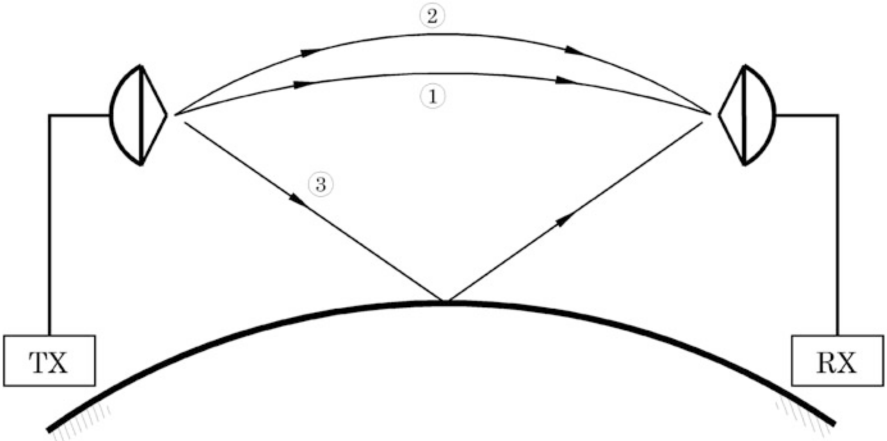


Fig. 7.15 Multipath simple concept in LOS radio link

7.7.4 Multipath

7.7.4.1 Introduction

Radiowaves in the line-of-sight communications are affected by several mechanisms like multipath between the transmitter and the receiver. It means that waves are received from different paths in the receiver because of reflections from the Earth surface and also because of air refraction index variation in the troposphere layer. A simplified concept of multipath reception is illustrated in Fig. 7.15.

Because of different path lengths for routes 1, 2, and 3 and also their angle of arrival, so amplitude and phase of the received signals are different, and even in some cases they are completely opposite. Based on this mechanism, the received signals will interact and sometimes attenuate each other severely resulting in multipath fading. The receiver detects the vector summation of these waves, and because of mutual interaction, sometimes the received signal is less than threshold, and since the received signal is about noise level, so it is not detectable. Therefore, the multipath fading is due to the multipath event and is a function of path length, frequency, and atmosphere condition.

Performance of digital and analog systems is not similar when they are subject to multipath fading. This phenomenon is more considerable in the medium- and high-capacity digital systems. In general, multipath effects are composed of the following distinctive types:

- Flat fading (FF)
- Selective fading (SF)

7.7.4.2 Flat Fading

Flat fading relates to the amplitude and phase variations of the received radiowaves when selective fading is zero. In low-capacity microwave digital systems, like 2, 8, and 17 Mb/s ones, flat fading is the significant factor. In other words, low-capacity digital system performance is similar to analog radio systems. In flat fading, all the frequency spectrum attenuation is the same, which means that wave spectrum after flat fading is similar to the original wave spectrum. In this case, total fading is equal to flat fading:

$$\mathrm{FM} = \mathrm{FFM} \tag{7.58}$$

7.7.4.3 Selective Fading

Several observations revealed that flat fading is not the only factor of degradation in medium- and high-capacity digital microwave signals. For an experimental radio link including 37 dB fade margin and the following characteristics:

- Capacity: 34 Mb/s
- Modulation: 4 PSK
- Path length: 70 km
- Frequency band: 2 GHz
- Basic bit error rate: $\mathrm{BER} = 10^{-4}$

Outages for $\mathrm{BER} \geq 10\mathrm{E}(-4)$ versus some specific flat fading are given in Fig. 7.16. Analysis of the long-term test results proved that there are some outages for flat fading less than 37 dB, i.e., in addition to flat fading, there is another fading which affects this radio link called selective fading.

The experiment results show that outages are mostly due to selective fading compared to the flat fading, so the received signal level is not a good basis for digital systems, and decision based only on flat fading is misleading and increasing fade margin will not improve the link performance effectively.

Figure 7.17 shows the inter-interference and selective fading, and it can be noted that in a limited band, the flat fading value is fixed in all the spectrum and the total fading is not fixed despite of having more than 10 dB variation.

One of the important factors in digital communication is the ratio of symbol duration to delay time of multipath. Increasing this value will decrease the interference (SF); therefore, low-capacity digital systems due to small bandwidth are not that much affected by SF, and so they are similar to FDM-FM analog systems, while high-capacity digital systems have more than tens of MHz bandwidth and as a result their symbol duration is very small and severely affected.

Selective fading in the digital radio systems is dependent on the following factors:

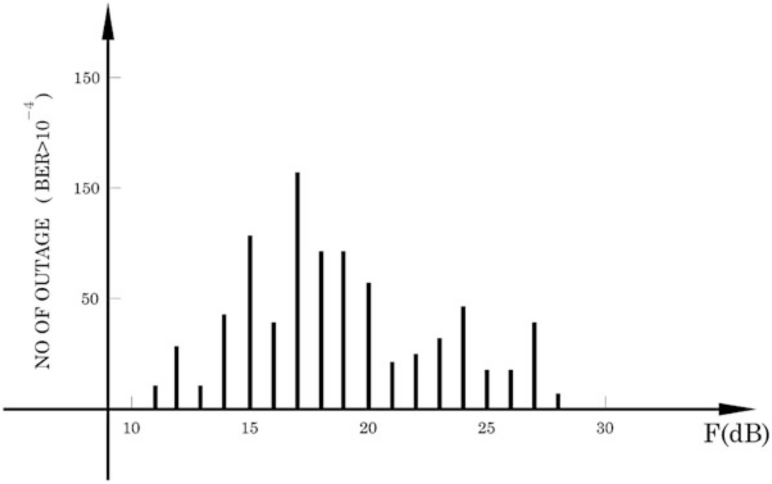


Fig. 7.16 Digital radio link outage vs. fading

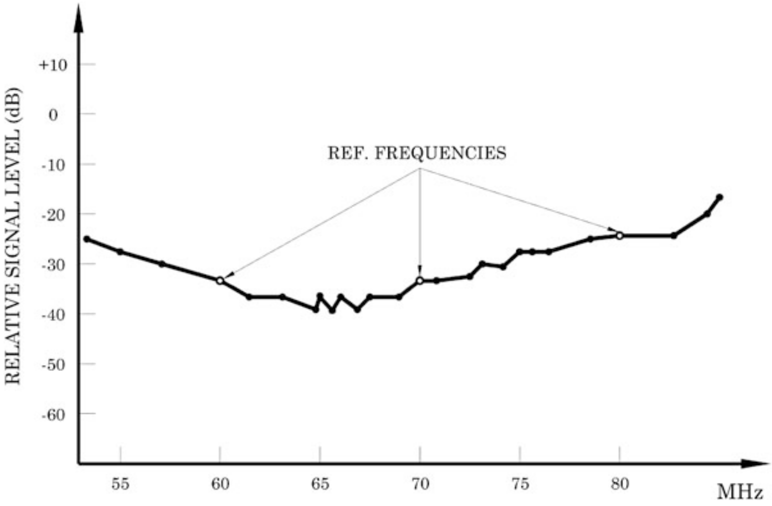


Fig. 7.17 Amplitude of a digital signal vs. frequency

- Digital radio system characteristic such as modulation type, capacity, and bandwidth and also radio equipment characteristic (*W* curve)
- Probability of selective fading which is a function of path length, atmosphere conditions, path roughness, antenna type, and open area criteria

Due to selective fading effect in medium- and high-capacity (like 34 Mb/s and upper) digital systems, we should define a new parameter instead of FFM called as net fade margin which is the basis of failure time calculation. Adaptive equalizer is usually used to combat the selective fading effects through considering the following points:

- Path length
- Atmosphere and climate conditions
- Modulation type
- System capacity
- RF channel bandwidth

7.7.5 Overreach Reception

Frequency planning is one of the major steps in a line-of-sight network design for which the outstanding points given below shall be observed:

- Limitation in the radio-frequency spectrum
- Ever-increasing demand for radio channels
- Expansion of radio services for more applications

Thus, national and international radio regulatory authorities follow the frequency reuse plan to the extent possible.

In a big fixed radio network, where, in addition to the main signal, the receiver detects some unwanted signals radiated from far station(s) within the same network and operating at the identical radio channel, the overreach reception will occur.

The LOS communications is one of the radio fields on which the frequency reuse plan may be applied by a well-engineered design. When the same RF channel is used in a network, there may be a co-channel interference because of the overreach mechanism. Even where different polarizations are employed for the same RF channel, the system is subject to the cross-polarization interference due to low antenna angle discrimination.

To explain overreach concept, as illustrated in Fig. 7.18, the transmitted radiowaves by station A at frequency f_1 in addition to receiving in station B are detected by station D through the overreach mechanism and acting as a noise source for it. The overreach undesirable signals are weaker than the main signal due to the following reasons:

- Transmitter antenna discrimination denoted as A_α because of the lower directivity of TX antenna in $\bar{AD}$ direction.
- Receiver antenna discrimination denoted as A_β because of the lower directivity of RX antenna in $\bar{AD}$ direction.
- Radiated power discrimination denoted as A_r, because of different TX output power and antenna gains in stations A and C.
- Distance discrimination denoted as A_d because of longer path for overreach signals equal to 20 log (AD/CD)

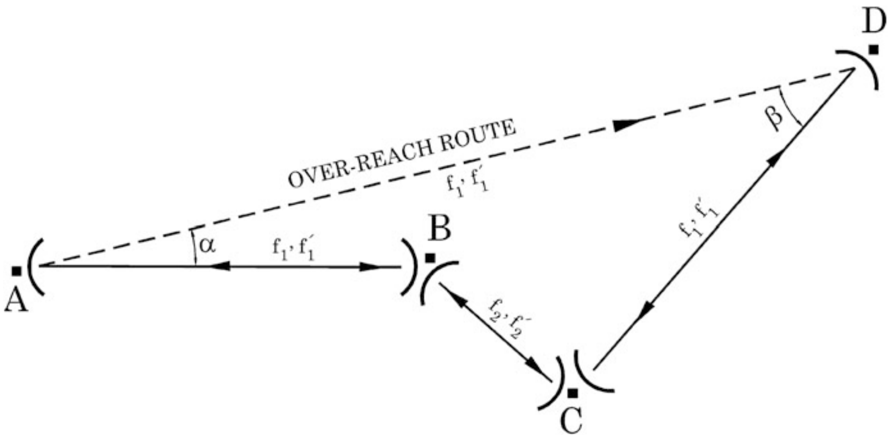


Fig. 7.18 Overreach geometry concept

- Obstruction discrimination denoted as A_o because of a potential obstacle existing on the overreach route, while on the main route it is in the line-of-sight condition

Considering the above assumptions, the ratio of main signal to overreach signal in terms of dB may be expressed as

$$[S/I]_{\mathrm{dB}} = A_\alpha + A_\beta + A_r + A_d + A_o \tag{7.59}$$

where all parameters are in dB.

If S/I value is greater than acceptable threshold value, then the interference is negligible, otherwise the interference should be decreased to the minimum value.

Usually in station site selection, the effects of natural obstacles will be considered and used to reduce the undesirable signal level.

These undesirable signals have destructive effects when there is a severe fading on the main path *CD* but no fading on the path $A\bar{D}$.

Example 7.10. According to Fig. 7.18 and the following assumptions,

$$A_\alpha = 15\,\mathrm{dB},\ A_\beta = 25\,\mathrm{dB}, AD = 110\,\mathrm{km},\ CD = 30\,\mathrm{km}$$
$$\mathrm{RSL} = -50\,\mathrm{dB}_m, \quad f = 7.5\,\mathrm{GHz}, \quad C/I \geq 18\,\mathrm{dB},\ \mathrm{min}$$

1. Is the main signal detected properly at station "D" when there is normal condition (i.e., no fading)?
2. Subject to 35 dB fading in the path *CD*, determine whether the signal is detected properly at D or not.

Solution. 1.

$$
\begin{aligned}
A_\alpha &= 15\,\text{dB}, \quad A_\beta = 25\,\text{dB}, \\
A_d &= 20\log\frac{AD}{CD} = 20\log\frac{110}{30} = 11.3\,\text{dB} \\
[S/I] &= A_\alpha + A_\beta + A_d = 51.3\,\text{dB}
\end{aligned}
$$

Therefore, the main signal is more than the minimum required threshold and is easily detectable.

2. A fading depth equal to 35 dB fading in the path CD will result in S/I reduction as follows:

$$(S'/I) = [s/I] - 35 = 16.3\,\text{dB}$$

Thus, the main signal cannot be received properly. ■

7.7.6 *Fading Occurrence Probability*

7.7.6.1 Main Parameters

The fading occurrence probability P_0 in the line-of-sight radiowave propagation is a function of the path length, frequency, geography, and climate expressed in a general form as follows:

$$P_o = \alpha \cdot G \cdot C \cdot F \cdot D^3 \tag{7.60}$$

where F is in GHz and D is in km and other parameters are specific to each method as explained in the following subsections:

$$P_0 = \alpha \cdot (\text{GC}) \cdot F \cdot D^3 \tag{7.61}$$

In the above equation, the GC factor and also α as a general coefficient should be determined in different calculation methods.

7.7.6.2 Calculation Methods

Different methods have been introduced to calculate fading occurrence probability. One of the initial models included is in ITU-R report 338 which is expressed by the following formula:

$$P_0 = \text{KQ} \cdot (\text{GC}) \cdot F \cdot D^3 \tag{7.62}$$

Comparing it with the general form indicates that $\alpha = 1$ and geoclimatic coefficient is assumed to be KQ. Typical values of KQ are reported in a table for different parts of the world. Because of new recommended methods by ITU, this method is not used anymore.

Another method is defined by the following equation:

$$P_0 = 0.3 \cdot A \cdot B \cdot (F/4)(D/50)^3 \tag{7.63}$$

where $\alpha = 0.3 \cdot (1/4) \cdot (1/50)^3 = 6 \times 10^{-7}$ and:

A: Terrain structure factor specified as follows:

- 0.25 for mountainous and highlands
- 1 for average terrain
- 4 for low-altitude, flat, and coastal regions

B: Climate factor specified as follows:

- 1 for dry climate
- 2 for temperate climate
- 4 for warm-humid climate

According to A and B values, geoclimatic factor range in formula (7.63) is from 0.25 to 16 with the following typical values:

- $AB = 16$ for coastal and low-altitude areas with high temperature and high humidity
- $AB = 4$ for low heights, low temperature, and high humidity
- $AB = 1$ for medium heights and humidity and temperate climate
- $AB = 0.25$ for mountainous, dry, and temperate area

In a large system design where the network is distributed in a vast region with a variety of terrain structure and climates, a chart similar to Fig. 7.19 should be prepared based on geographical and meteorological data to indicate geoclimatic factor.

Example 7.11. In a 45 km line-of-sight radiocommunication link working in 6 GHz band, find fading occurrence probability in the following cases:

1. In a country with $KQ = 2.6 \times 10^{-6}$
2. In a mountainous area with dry and temperate climate

Solution. 1. Using Eq. (7.62) and given data yields

$$KQ = 2.6 \times 10^{-6}, \quad F = 6\,\text{GHz}, \quad D = 45\,\text{km} \quad \Rightarrow \quad P_0 = 0.14$$

2. For the mentioned region, geoclimatic factor (AB) may be assumed 0.25. Using Eq. (7.63) and given data yields

$$F = 6\,\text{GHz}, \quad D = 45\,\text{km} \quad \Rightarrow \quad P_0 = 0.082$$

■

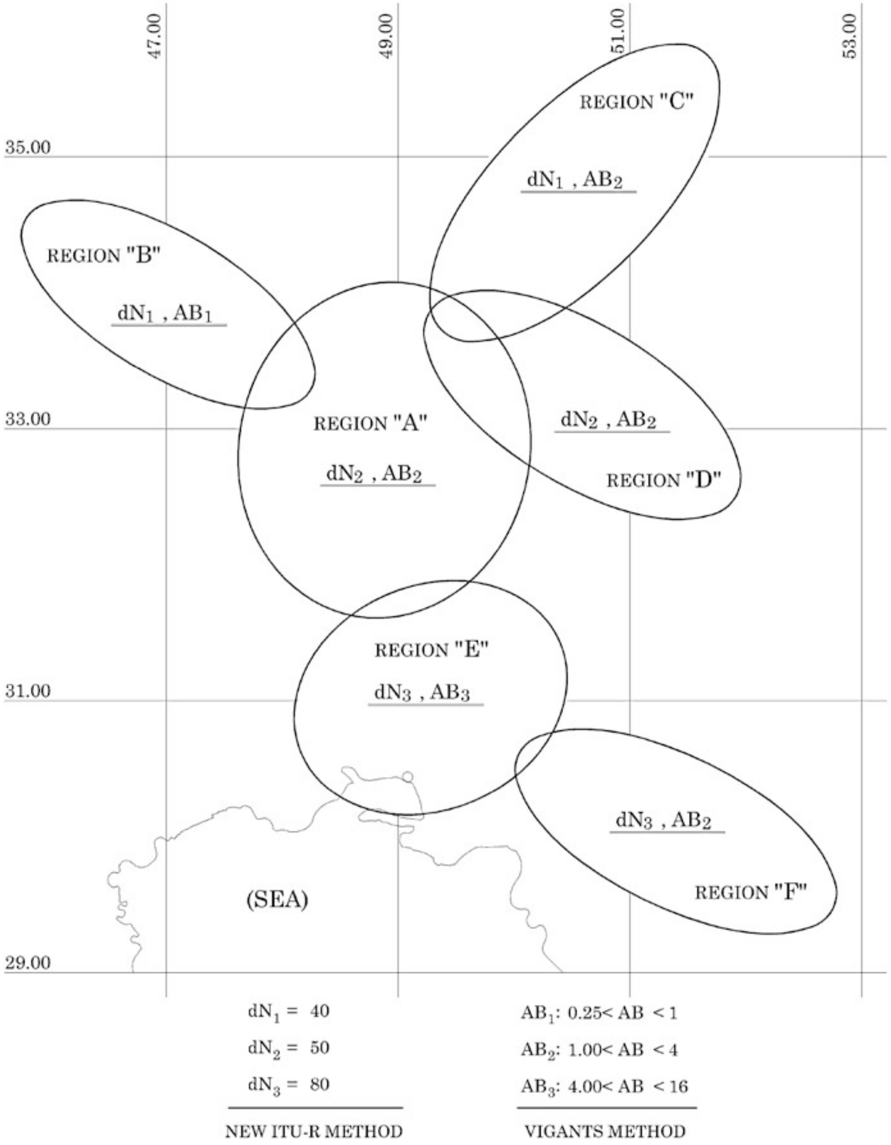


Fig. 7.19 A typical geoclimatic coefficient

The Vigants and Barnett method as a popular procedure is described by following equation:

$$P_0 = 10^{-7} \cdot A \cdot B \cdot F \cdot D^3 \tag{7.64}$$

Here, $\alpha = 10^{-7}$, A, and B are similar to the previous method with similar values. It should be noted that Eq. (7.63), which estimates fading occurrence probability six times more than the Vigants and Barnett method, is usually employed for microwave systems with medium and high capacity, while Eq. (7.64) is normally used in P-MP and microwave systems with low capacity.

7.7.7 New ITU-R Method

7.7.7.1 Fading Mechanisms

We will deal with ITU-R new method to calculate fading occurrence probability which was introduced in the tenth edition of the recommendation P.530 issued in 2005. This method is subject to further improvements in the future. As mentioned in the previous section, most factors affecting the received signal level variations in radio links are:

- Air refraction variations and K-factor
- Terrain roughness and the height of TX/RX antennas

Air refraction variations for altitudes up to 65 m from the Earth surface denoted as ΔN or dN have been prepared by the ITU-R P.453 recommendation covering the whole world on seasonal basis.

Various clear-air fading mechanisms caused by extremely refractive layers in the atmosphere must be taken into account in the planning of links with a length more than a few kilometers. Among the fading mechanisms, beam spreading (commonly referred to as defocusing), antenna decoupling, surface multipath, and atmospheric multipath are more common. Most of these mechanisms can occur by themselves or combined together.

A particularly severe form of frequency selective fading occurs when beam spreading of the direct signal combines with a surface-reflected signal to produce multipath fading. Scintillation fading due to smaller-scale turbulent irregularities in the atmosphere is always present with these mechanisms, but at frequencies below 40 GHz, its effect on the overall fading distribution is not significant.

A method for predicting the single-frequency (or narrowband) fading distribution at large fade depths in the average worst month in any part of the world is given in Sect. 7.7.7.2. This method does not make use of the path profile and can be used for the initial planning, licensing, or design purposes. Also, a second method is introduced in Sect. 7.7.7.3 which is intended to be employed for all fade depths. This method is suitable for large fade depths and an interpolation procedure for small fade depths.

In addition to the above methods, reference is made to the following issues which are expressed in the ITU-R P.530:

- Prediction method for enhancement
- Conversion from average worst month to average annual distributions
- Conversion from average worst month to shorter worst periods of time

- Prediction of nonselective outage
- Occurrence of simultaneous fading on multi-hop links

7.7.7.2 Small Percentages of Time

To predict the outage occurrence probability for small percentages of time, the following step-by-step procedure may be used:

Step 1. For the path location in question, estimate the geoclimatic factor K (other than atmospheric K-factor) for the average worst month from fading data for the geographic area of interest if these are available.

If measured data for K are not available and a detailed link design is being carried out, estimate the geoclimatic factor for the average worst month from

$$K = 10^{(-3.9-0.003 dN_1)} \cdot S_a^{-0.42} \tag{7.65}$$

where dN_1 is the point refractivity gradient in the lowest 65 m of the atmosphere not exceeding for 1 % of an average year and S_a is the area terrain roughness.

dN_1 is provided on a 1.5° grid in latitude and longitude in recommendation ITU-R P.453 given in Figs. 7.20, 7.21, 7.22, and 7.23. The correct value for the latitude and longitude at path center should be obtained from the values for the four closest grid points by bilinear interpolation. The data are provided in a tabular format and are available in the Radiocommunication Bureau (BR).

S_a is defined as the standard deviation of terrain heights (m) within a 110 km × 110 km area with a 30 s resolution (e.g., the Globe "gtopo30" data). The area should be aligned with the longitude, such that the two equal halves of the area are on each side of the longitude that goes through the path center. Terrain data are available from the web address provided by the BR.

If a quick calculation of K is required for planning applications, a fairly accurate estimate can be obtained from

$$K = 10^{-(4.2+0.0029 dN_1)} \tag{7.66}$$

Step 2. From the antenna heights h_e and h_r (above sea level in m), calculate the magnitude of the path inclination $|\epsilon_p|$ (mrad) from

$$|\epsilon_p| = |h_r - h_e|/D \tag{7.67}$$

where D is the path length in km.

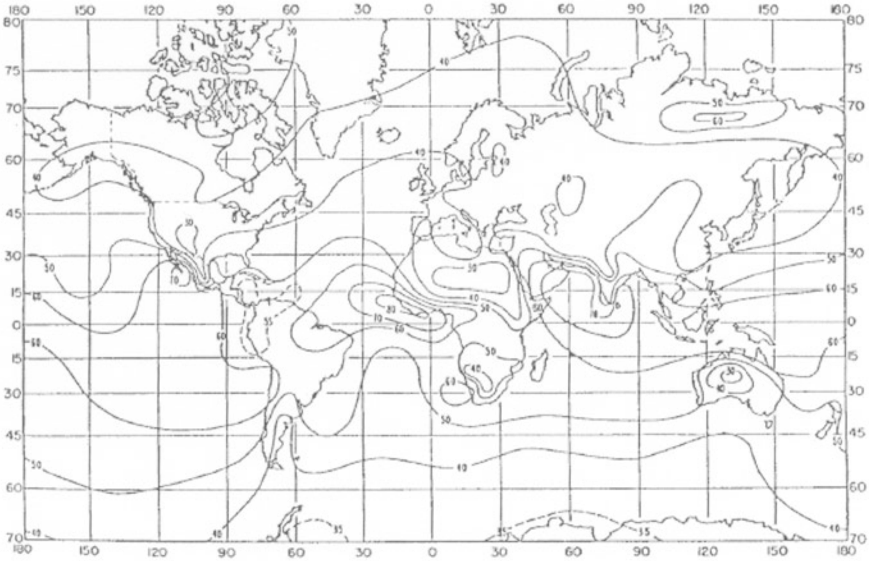


Fig. 7.20 Average ΔN contours in winter (Ref.: ITU-R, P.453)

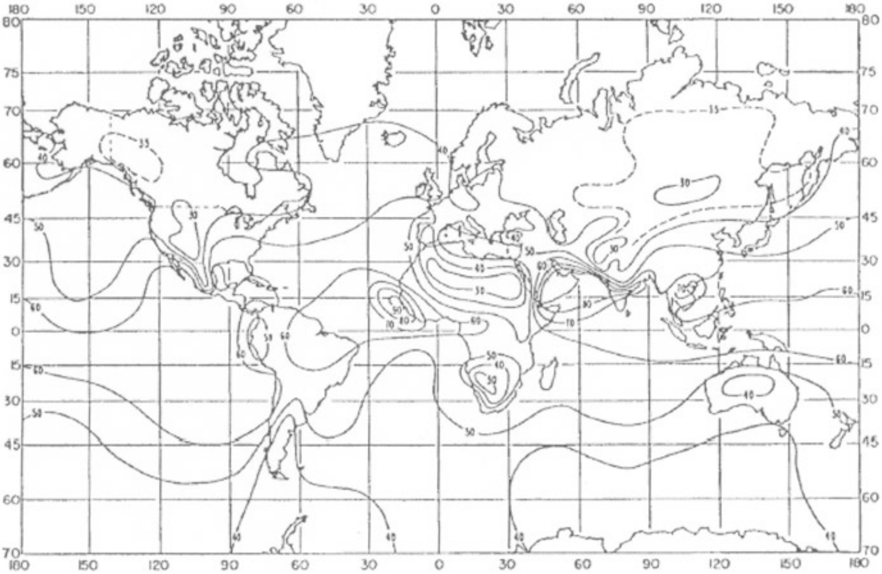


Fig. 7.21 Average ΔN contours in spring (Ref.: ITU-R, P.453)

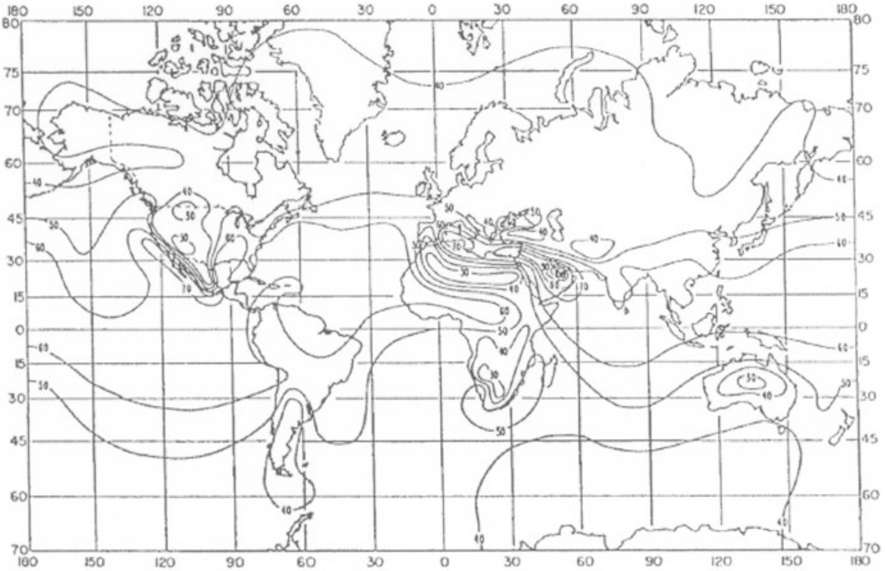


Fig. 7.22 Average Δ*N* contours in summer (Ref.: ITU-R, P.453)

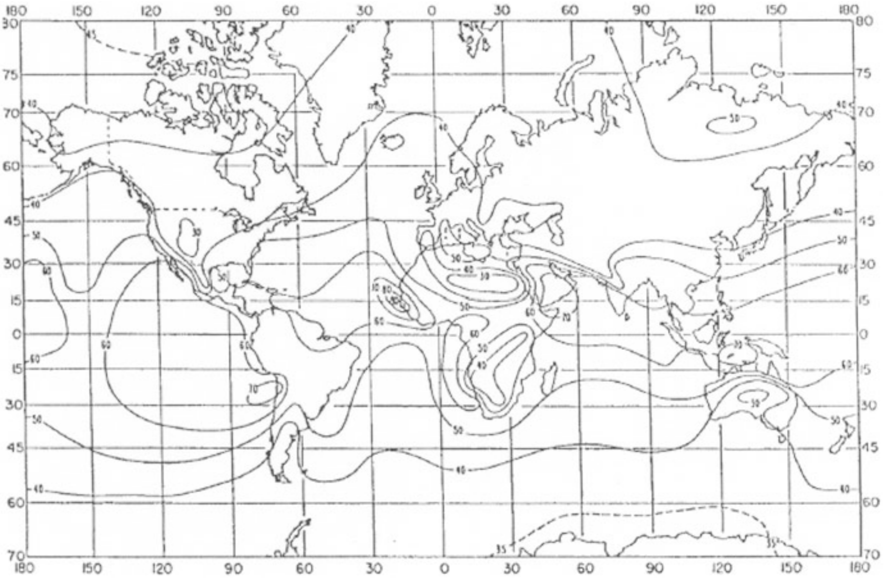


Fig. 7.23 Average Δ*N* contours in autumn (Ref.: ITU-R, P.453)

Step 3. For detailed link design applications, calculate the percentage of time p_w that fade depth A (dB) = FM (dB) is exceeded in the average worst month from

$$p_w = KD^{3.2}(1 + |\epsilon_p|)^{-0.97} \times 10^{(0.032f - 0.00085h_L - A/10)}\ \% \tag{7.68}$$

where f is the frequency (GHz), h_L is the altitude of the lower antenna (i.e., the smaller of h_e and h_r), and the geoclimatic factor K is obtained from Eq. (7.65).

For quick planning applications, calculate the percentage of time P_w that fade depth A (dB) is exceeded in the average worst month from

$$P_w = KD^{3.0}(1 + |\epsilon_p|)^{-1.2} \times 10^{(0.033f - 0.001h_L - A/10)}\ \% \tag{7.69}$$

where K is obtained from Eq. (7.66).

Note 1.

The overall standard deviations of error in predictions using Eqs. (7.65), (7.66), (7.68), and (7.69) are 5.7 dB and 5.9 dB, respectively (including the contribution from year-to-year variability). Within the wide range of paths included, a maximum value of 7.3 dB can be calculated for overwater paths. However, the small difference between the overall standard deviations does not accurately reflect the improvement in predictions which are available, using Eqs. (7.65) and (7.68) for links over very rough terrain (e.g., mountains) or very smooth terrain (e.g., overwater paths). For example, standard deviations of error for mountainous links ($h_L > 700$ m) are reduced by 0.6 dB and for individual errors of links over high mountainous regions by up to several decibels.

Note 2.

Equations (7.68) and (7.69) and the associated Eqs. (7.65) and (7.66) for the geoclimatic factor K were derived from multiple regressions on fading data for 251 links in various geoclimatic regions of the world with path lengths D in the range of 7.5–185 km, frequencies f in the range of 450 MHz to 37 GHz, path inclinations $|\epsilon_p|$ up to 37 mrad, lower antenna altitudes h_L in the range of 17–300 m, refractivity gradients dN_1 in the range of -860 to -150 N-unit/km, and area surface roughness S_a in the range of 6–850 m (for $S_a < 1$ m, use a lower limit of 1 m).

Equations (7.68) and (7.69) are also expected to be valid for frequencies up to at least 45 GHz. The results of a semiempirical analysis indicate that the lower-frequency limit is inversely proportional to the path length. A rough estimate of this lower-frequency limit, $f_{\min}$, can be obtained from

$$f_{\min} = 15/D \text{ GHz} \tag{7.70}$$

7.7.7.3 All Percentages of Time

The method given below for predicting the percentage of time in which any fade depth is exceeded combines the deep-fading distribution given in the preceding section and an empirical interpolation procedure for shallow fading down to 0 dB.

Step 1. Using the method in (7.7.7.2), calculate the multipath occurrence factor, p_0 (i.e., interception of the deep-fading distribution with the percentage of time axis):

$$p_0 = KD^{3.2}(1 + |\epsilon_p|)^{-0.97} \times 10^{(0.032f - 0.00085h_L)}\ \% \tag{7.71}$$

For detailed link design applications, with K obtained from Eq. (7.65),

$$p_0 = KD^{3.0}(1 + |\epsilon_p|)^{-1.2} \times 10^{(0.033f - 0.001h_L)}\ \% \tag{7.72}$$

For quick planning applications, with K obtained from Eq. (7.66), note that Eqs. (7.71) and (7.72) are equivalent to Eqs. (7.68) and (7.69), respectively, with $A = 0$.

Step 2. Calculate the value of fade depth, A_t, at which the transition occurs between the deep-fading distribution and the shallow-fading distribution as predicted by the empirical interpolation procedure:

$$A_t = 25 + 1.2\ \log\ p_0\ \text{dB} \tag{7.73}$$

The procedure now depends on whether A is greater or less than A_t.

Step 3a. If the required fade depth, A, is equal to or greater than A_t:
Calculate the percentage of time that A is exceeded in the average worst month:

$$p_w = p_0 \times 10^{-A/10}\ \% \tag{7.74}$$

Note that Eq. (7.74) is equivalent to Eq. (7.68) or (7.69), as appropriate.

Step 3b. If the required fade depth, A, is less than A_t:
Calculate the percentage of time, p_t that A_t is exceeded in the average worst month:

$$p_t = p_0 \times 10^{-A_t/10}\ \% \tag{7.75}$$

Note that Eq. (7.75) is equivalent to Eq. (7.68) or (7.69), as appropriate, with $A = A_t$.

Calculate q'_a from the transition fade A_t and transition percentage time p_t:

$$q'_a = -20 \log_{10} \{-\ln[(100 - p_t)/100]\} / A_t \tag{7.76}$$

Calculate q_a from q'_a and the transition fade A_t:

$$q_t = (q'_a - 2)/[(1 + 0.3 \times 10^{-A_t/20})10^{-0.016A_t}] - 4.3(10^{-A_t/20} + A_t/800) \tag{7.77}$$

Calculate q_a from the required fade A:

$$q_a = 2 + [1 + 0.3 \times 10^{-A/20}][10^{-0.016A}][q_t + 4.3(10^{-A/20} + A/800)] \tag{7.78}$$

Calculate the percentage of time, p_w, that the fade depth A (dB) is exceeded in the average worst month:

$$p_w = 100[1 - \exp(-10^{-q_a A/20})]\ \% \tag{7.79}$$

Provided that $p_0 < 2000$, the above procedure produces a monotonic variation of p_w versus A which can be used to find A for a given value of p_w using simple iteration.

With p_0 as a parameter, Fig. 7.24 gives a set of curves providing a graphical representation of the method.

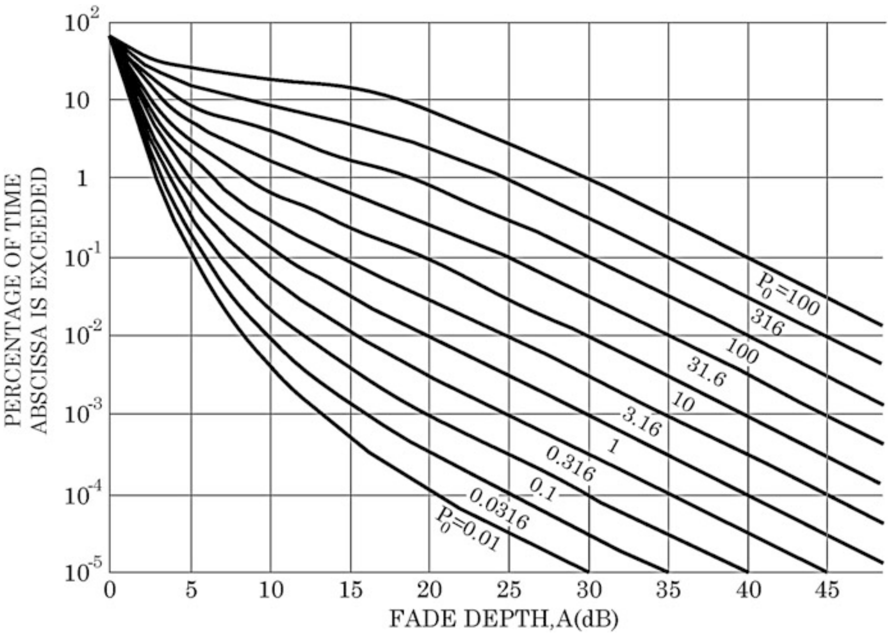


Fig. 7.24 Percentage of time, p_w, fade depth, A, exceeded (in an average worst month) (Ref.: ITU-R, P.530)

Example 7.12. Considering the radio link defined in example (7.12), with $f = 6$ GHz and $D = 45$ km, find:

1. Climate factor in a region with $dN = 70$
2. Fading occurrence probability if the station height from sea level is 1000 m and 1400 m, respectively

Solution. 1. Using Eq. (7.66) to find K,

$$K = 10^{-4.2-0.0029\times(-70)} \approx 10^{-4}$$

2.

$$\begin{aligned} \epsilon_p &= \frac{1400-1000}{45} = 8.9\,\text{m/km} \\ h_L &= 1000\,\text{m} \end{aligned}$$

Using Eq. (7.69), it is concluded:

$$\begin{aligned} P_0 &= 10^{-4} \times 45^3 \times (1+8.9)^{-1.2} \times 10^{(0.033\times 6-1)} \\ P_0 &= 0.092\,\% \end{aligned}$$

■

7.8 Outage Time

7.8.1 Introduction

For a 2500 km hypothetical reference radio network, the availability criterion (denoted as A) was suggested to be between 99.5 and 99.9 % in Sect. 7.6. This availability criteria is equivalent to 0.5–0.1 % unavailability denoted as U % which is about 526–2630 min outage in a year.

In radio network design, the time unavailability budget, say the annual unavailability budget, should be divided into different effective factors. In radio systems, this ratio should be defined relative to each link.

7.8.2 Fade Margin

As a countermeasure to combat the short-term temporal variations of the received signal level, some safety allowance called fade margin (FM) should be considered. For the large and high-capacity networks, this factor is about 30–40 dB, and in small and low-capacity networks and point-to-multipoint (P-MP) systems, it is between 15 and 30 dB.

In the case that fading loss is greater than fade margin, fading is called deep fading which will cause severe failure resulting in the link outage. Based on this, the equation of deep-fading occurrence probability denoted as P_w will be

$$P_w = P_0 \times 10^{-\mathrm{FM}/10} \tag{7.80}$$

In Eq. (7.80), P_0 is the fading occurrence probability and FM is link fade margin in terms of dB. For example, deep-fading occurrence probability based on the Vigants–Barnett method is

$$P_w = 10^{-7} \cdot A \cdot B \cdot F \cdot D^3 \times 10^{-\mathrm{FM}/10} \tag{7.81}$$

In the design of large LOS networks consisting of a number of radio links, first the total unavailability budget shall be divided into each radio hop. Then a reasonable portion of it shall be allocated to the propagation outages due to adverse conditions such as deep fadings, sharp multipath, radio path blockage, severe rainfall, etc.

Example 7.13. If, in the previous example, it is desired to have fade margin equal to FM = 35 dB, find the deep-fading occurrence probability.

Solution.

$$P_w = P_0 \times 10^{-\mathrm{FM}/10}$$

$$\Rightarrow P_w = 0.092 \times 10^{-3.5} = 2.9 \times 10^{-5}$$

■

7.8.3 Link Outage Time

Outage time of each link due to radiowave propagation is

$$T_0 = P_w \times T_r \tag{7.82}$$

In the above equation:

T_0: Link outage time in a period of T_r
P_w: Deep-fading occurrence probability
T_r: Reference time duration

As the outage in radiowave propagation is equivalent to the link unavailability, so it is concluded that

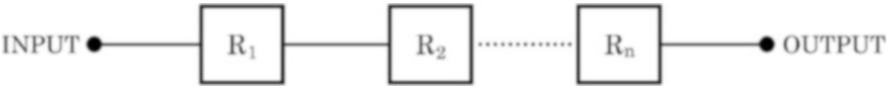


Fig. 7.25 Typical overall cascade radio network

$$U = P_w = P_0 \times 10^{-\mathrm{FM}/100} \tag{7.83}$$

The availability of a radio link sometimes referred to the link propagation reliability index; therefore:

$$R = 1 - U \tag{7.84}$$

$$R\,\% = (1 - U) \times 100 \tag{7.85}$$

In accordance with Fig. 7.25, to calculate the radiowave propagation reliability coefficient of a path which is composed of some consecutive links, all the path should be in acceptable conditions; it means that

$$R = R_1 \times R_2 \times \cdots \times R_n = \prod_1^n R_i \tag{7.86}$$

$$R = (1 - U_1)\,(1 - U_2)\cdots(1 - U_n) \tag{7.87}$$

As the U_i values are small, we can neglect components including $U_i \times U_j$ (second order or higher), so Eq. (7.84) will be simplified as follows:

$$R = 1 - U_1 - U_2 - \cdots - U_n = 1 - \sum_1^n U_i \tag{7.88}$$

Example 7.14. A network consists of three links with 20, 25, and 40 km path lengths, if the fading occurrence probability in the 20 km link is 0.02 %.

1. Find the fading occurrence probability in the other links.
2. If fade margins of these links are 30 dB, 35 dB, and 40 dB, respectively, find the deep-fading occurrence probability of each link and also the whole network.
3. Find the network outage time.

Solution. 1.

$$d = 20\,\mathrm{km} \Rightarrow P_0 = 0.02$$

As the P_0 value is related to third-order exponent of the path length, so

$$\begin{aligned} d' &= 25\,\mathrm{km} \Rightarrow P_0' = P_0 \times \frac{25}{20}^3 \Rightarrow P_0' = 0.039 \\ d'' &= 40\,\mathrm{km} \Rightarrow P_0'' = P_0 \times \frac{40}{20}^3 \Rightarrow P_0'' = 0.16 \end{aligned} \tag{7.89}$$

2.

$$\begin{aligned} &P_w = P_0 \times 10^{-\mathrm{FM}/10} \Rightarrow P_w = \ 2 \times 10^{-5} \\ &P_w' = P_0' \times 10^{-\mathrm{FM'}/10} \Rightarrow P_w' = \ 0.039 \times 10^{-3.5} = \ 1.23 \times 10^{-5} \\ &P_w'' = P_0'' \times 10^{-\mathrm{FM''}/10} \Rightarrow P_w'' = \ 1.6 \times 10^{-5} \\ &U = P_w + P_w' + P_w'' = 4.83 \times 10^{-5} \end{aligned}$$

3.

$$\begin{aligned} &T_0 = U \times T_r \to T_0 = 4.83 \times 10^{-5} \times 30 \times 24 \times 60 \\ &T_0 = 2.087\,\text{min per month} \end{aligned}$$

■

7.8.4 Fade Margin Calculation

The step-by-step fade margin calculation method of network with a desirable availability requirement is explained below:

Step 1. Select the hypothetical reference unavailability budget based on the specified requirements.

Step 2. Divide the unavailability budget between different effective factors and fix the radiowave propagation unavailability budget of hypothetical reference circuit.

Step 3. Divide the radiowave propagation unavailability budget between different links considering the network structure and then find the deep-fading occurrence probability of desirable link denoted as P_w.

Step 4. Find the fading occurrence probability of desirable link denoted as P_0 based on link characteristic.

Step 5. Find the fade margin (FM) using Eq. (7.80).

Example 7.15. Find the fade margin for a radio link of 50 km path length working in mountainous area with dry weather and operating at 8 GHz. Assume 0.1 % unavailability budget for the hypothetical circuit.

Solution. The acceptable unavailability of this link is

$$U_R = 0.001\, P_w = 0.001 \times \frac{50}{2500} = 0.00002$$

Using Eq. (7.63) and area climatic conditions, the following results are concluded:

$$\text{(Area conditions)} \quad \Rightarrow \quad A = 0.25 \quad \text{and} \quad B = 1$$

$$P_0 = 6 \times 10^{-7} \times 0.25 \times 1 \times 8 \times (50)^3 \quad \Rightarrow \quad P_0 = 0.15$$

$$P_w = P_0 \times 10^{-\mathrm{FM}/10} = 1.33 \times 10^{-4}$$

$$\mathrm{FM}/10 = 3.87 \quad \Rightarrow \quad \mathrm{FM} = 38.7\,\mathrm{dB}$$

■

7.9 Design Considerations

Major design and engineering considerations for the terrestrial line-of-sight radio links are outlined in this section.

7.9.1 Design Criteria

To plan a new radio network, first of all, design criteria shall be set by the engineering group. From propagation points of view, the following main issues should be studied carefully and appropriate decisions be made:

- Telecom traffic which needs to include initial requirements and ultimate RF channel capacity considering all potential expansion objectives in the system backbone and spur links
- Selected modulation type(s) in the backbone and spur links for fixing the RF channel bandwidth and frequency utilization efficiency
- Grade of the network including local, medium, and high levels
- Frequency band(s) and RF channel arrangement including frequency reuse policy

- Availability, reliability, quality, and performance requirements including related criteria
- Apportionment of unavailability budget between a number of items including outages due to propagation adverse effects
- Preferred improvement techniques considering technical requirements and regulatory constraints
- Geoclimatic conditions and variation range of K-factor
- Existing or planned radio networks in the new project area considering their main technical aspects

7.9.2 Radio Site Selection

In the terrestrial line-of-sight radio networks, the terminal stations are located in dedicated points based on operational and traffic requirements such as residential areas, industrial plants, and towns without considerable flexibility. On the other hand, repeater site selection is highly flexible and dependable on the local conditions, terrain topography, and design group experience.

Due to the considerable cost, operational and maintenance impacts, quantity, and locations of the repeater stations are very important, and in general the following issues shall be observed for the site selections:

- Station land acquisition
- Short access road
- Distance from maintenance center
- Quantity of repeaters
- Distance from public electric power network
- Ground and soil condition for tower and building
- Radio tower height

7.9.3 Foundations and Earthling Network

To select the best path based on ground structure, the following points should be considered:

- Mountainous path selection due to the preference of these paths to others
- Avoidance of paths in coastal, low-height, and vast field regions

Terrain structure of radio path is a key point regarding propagation effects. For a well-engineered link, the following objectives shall be taken into account:

- Mountainous terrain is preferred because of its antireflective nature and providing fair mixed air.

In the line-of-sight radio links, horizontal paths are not desirable especially when the altitude of stations is low. This is because of probability for the radiowaves being trapped inside atmospheric ducts and strong Earth surface reflections as well. To avoid adverse effects of these mechanisms, the following points are advised:

- Low heights, coastal areas, and along rivers are not recommended.
- Radio paths over the lakes, seas, and vast steppes should be avoided to the extent possible.
- Highly reflective surfaces, either natural or artificial, along the radio path are undesirable.

7.9.4 Climate

The appropriate climate for radiowave propagation in the LOS links are:

- Moderate temperature
- Dry or low humid climate
- Mild wind
- Low rain at frequencies lower than 10 GHz.

High humidity and high temperature air should be avoided because of forming atmospheric duct.

7.9.5 Radio Path Inclination

In the line-of-sight radio links, horizontal path is not desirable because of high probability of being trapped inside an atmospheric duct or creating a strong reflection as well. To avoid destructive effects of this situation, it is advised to select high and low adjacent stations to provide sufficient vertical inclination in the radio path. A rough criterion in this regard is 5 m/km vertical inclination equal to 5 mrad particularly in the coastal areas.

7.9.6 Zigzag Path

Since the number of RF channels is limited in each frequency sub-band, the national radio authorities are reluctant in the assignment of many RF channels where the users can handle their requirements based on the “frequency reuse” policy. On the other hand, the LOS radio networks are subject to the following negative mechanisms which potentially can result in co-channel frequency interference:

- Overreach
- Diffraction

Normally for solving the mentioned problems in a proper and professional manner, experienced designers select zigzag paths to provide better angle discrimination between main radio path and unwanted paths. By applying this method, lower number of RF channels are required in radio networks including numerous radio hops.

7.9.7 Path Length

Path length of each radio hop has the following contradicting effects on the overall network:

- By increasing the path length, the effective K-factor will increase and approach to one (see Fig. 7.3).
- By increasing the path length, the deep-fading occurrence probability will increase resulting in lower performance and higher outage time.
- Increasing the path length will reduce total number of repeater stations in each network resulting in failure points.
- Increasing the average hop path length will reduce the initial capital investment for the overall network.

Thus, the well-engineered process in the LOS radio network design includes trade-off between a number of issues such as maintenance, reliability/availability, initial investment, and running costs considering the network site-specific conditions.

7.9.8 Antenna Around Clearance

As mentioned in Sect. 7.4.8, there should not be any obstacles in a specific distance around the antenna.

7.9.9 Radio Sources

The station location should be far from the following radio sources:

- Terrestrial satellites transmitters
- TV transmitters
- Radar stations

Especially, distance from the radar stations is more important due to high transmitter output power (several 10 kW) and rotating high-gain antenna. Because of powerful signal and radiating in the same radio frequency channel, these stations will produce undesirable signal as a limiting factor for proper operations.

7.9.10 Precipitation

In general, the rain attenuation at frequencies lower than 8 GHz is negligible, its effects on radiowaves at frequencies between 8 and 10 GHz and heavy rain can be considerable and at frequencies higher than 10 GHz significant, and it should be calculated based on ITU-R recommendation P.530 and the formula and conditions set in Chap. 2 as well. It should be noted that during the rain, there is no undesirable effects of deep fading due to other atmospheric factors, because of forming homogeneous condition based on well-mixed air.

7.9.11 Improvement Techniques

To reduce the deep-fading occurrence probability, undesirable effects of wave propagation, and link outage, using the improvement techniques including the following types is recommended:

- Antenna space diversity (SD)
- Hybrid diversity (HD)
- RF channel diversity (in one band) (FD)
- Cross band diversity
- Combined frequency and space diversity (FD + SD)

More details regarding the above diversity techniques are given in other chapters.

7.9.12 Technical Calculations

For the propagation engineering of the LOS radio networks, a number of technical calculations should be performed, among which the following items are more common:

- Path calculation considering clearance criteria
- Free-space loss
- Flat, selective, and net fadings to fix the required fade margin
- Power budget calculation to determine equipment or material dimensions
- Availability/unavailability calculation
- Hop, section, and system performance calculation
- Precipitation losses based on local data
- Passive reflector configuration, size, and angles
- Deep-fading occurrence probability and annual outage time
- Radio-frequency interference

7.10 Summary

Main propagation mechanisms and engineering issues in the terrestrial line-of-sight (LOS) radio links were studied, and required explanations, illustrations, formulas, and examples were provided in this chapter, including:

- Propagation environment and main affecting factors such as different types of attenuations, adverse mechanisms, and precipitation were introduced.
- Most common frequency bands used in the terrestrial line-of-sight communications were stated.
- Radiowave trajectory in the LOS radio links and its curvature due to the air refraction variations were discussed.
- K-factor was defined and its relation with vertical gradient of refractivity was explained and related formulas extracted.
- Different values of K-factor and subsequent effects on the radiowave propagation were discussed, and its typical values were specified for the terrestrial LOS communications.
- Radio path profiles and its modified versions were introduced, and common types used for radio link analysis and design were determined.
- Diffraction loss due to obstruction was explained, equation for radius of the first Fresnel zone was given, and formulas related to knife-edge and rounded obstacles were specified.
- Radio path clearance criteria in the LOS radio links for single and double antennas were stated, and conditions for optimum height of antenna centerlines were discussed.
- Directional antennas around clearance conditions were examined for the LOS radio links.
- Propagation losses resulting in a typical radio link were examined, and link power budget equation was specified.
- Various sources of propagation attenuations, in addition to free-space loss, were discussed.
- Practical procedure to predict the rain loss based on the ITU-R recommendation was introduced, and required steps for calculation including frequency and polarization scaling were specified.
- Deterioration of radiowaves subject to cross-polarization mechanism was defined, and the step-by-step method for calculation of outages due to this phenomenon either in clear air or during rain was explained.
- Hypothetical reference circuit for terrestrial digital LOS radio links based on the ITU-R recommendation was introduced, and related criteria for the network main parameters such as availability, unavailability, quality, and system performance were specified based on this circuit.
- Media permanent and occasional attenuations in radiowave propagation were listed, and the fading process including multipath, flat, and selective fades was described.

- Overreach reception and affecting parameters were studied, and the related equation for signal to interference ratio was derived.
- Different methods for calculation of fading occurrence probability including conventional, Vigants–Barnet, and new ITU-R methods were given.
- Link outage estimation method was defined and required fade margin calculation stated.
- Practical considerations in radio link design including site selection, terrain structure, climatic conditions, path inclination, zigzag path effects, path length, antenna around clearance, radio interference sources, precipitation, improvement techniques, and required calculations were outlined.

7.11 Exercises

Question

1. Define the line-of-sight radiocommunications and effects of K-factor in these communications and list several examples for this type of communications.
2. Define the wave propagation environment in line-of-sight radiocommunications and list the important effective factors of this type of wave propagation.
3. List the common frequency bands in LOS communications and list the main phenomenon in these communications.
4. Explain how Eq. (7.4) is simplified to Eq. (7.6).
5. Define the K-factor and its effects in wave path radius.
6. Define the different atmosphere conditions.
7. Find K_s, K_e, and K_m in a 50 km path length at 8 GHz frequency in LOS communications according to Fig. 7.3.
8. State the radio path profile applications and list the methods they are provided and explain their applications.
9. Prove Eq. (7.13).
10. Verify the radio path clearance criteria and explain effects of the following factors on it:
    - Frequency band
    - Number of obstacles and their distributions
    - Climate conditions
11. What are the reasons for using diversity antennas in the LOS communications?
12. List the major factors affecting the optimum height of antenna centerline.
13. List main preoperational attenuations involved in a typical line-of-sight (LOS) radio link.
14. Fade margin considered for a typical LOS radio link in the SHF/EHF band is 38 dB; if the propagation loss value for a rainy case is to be 25 dB, specify whether a reliable communication can be guaranteed or not. What about the multipath fading occurrence probability when there is heavy rain?

15. Define the cross-polarization discrimination reduction in rain condition.
16. Specify the conditions that angle of arrival in receiver antenna or angle of launch in transmitter antenna variations intensifies.
17. Explain the different methods of deep-fading occurrence probability calculation in terrestrial microwave communications and mention the corresponding equations.
18. Specify the hypothetical references of fixed radiocommunications and answer the following questions in this regard:
    (a) Hypothetical reference applications
    (b) The last changes in ITU regulation documents
19. Define the unavailability budget and the effective factors on it and the corresponding classification.
20. Define the main design criteria in LOS radio networks and explain each of them based on ITU-R recommendations.
21. Define the difference between radio system availability criteria and wave propagation reliability coefficient and their ranges in corresponding networks.
22. Define unavailability budget in radio networks and its classification.
23. Explain the difference between quality criteria, performance criteria, and wave propagation reliability coefficient. Define their corresponding criteria.
24. Explain fading and deep-fading phenomena in networks and list the requirements in radio network design to combat deep fading.
25. Define the difference among flat fading, frequency selective fading, and net fading. In which radiocommunication systems they are more effective?
26. Explain overreach mechanism and its effects. Also, list methods to combat the adverse effects of this phenomenon.
27. Define the effective factors in LOS radio networks fading and state the corresponding equation.
28. List the fading occurrence probability calculation methods.
29. Define how the climate factors should be considered in different fading occurrence probability calculation methods.
30. List the effects of the following factors in fading occurrence probability:
    - Path inclination
    - Station height
    - Radio frequency
    - Path length
31. What are the link outage conditions in digital radio systems? Express effective factors in the outage time.
32. Explain the appropriate method of required fade margin calculation for LOS radio networks.
33. List the major issues in the site selection of a repeater station.
34. What are suitable climatological condition in the LOS radiowave propagation?
35. Discuss about conditions required to avoid atmospheric ducts in the LOS communications and express the approximate criterion for it.

Problems

1. Refraction index is related to height by the following equation:

$$n(h) = 1 + 3.16 \times 10^{-4} \cdot e^{-0.136h}$$

where h is in km; find:

(a) Refraction index in 200 and 1200 m above the ground level
(b) Radius of the radio path curvature
(c) K-factor

2. Find the K-factor in the following conditions:

(a) Standard conditions $N' = -39$
(b) Over-standard conditions $N' = -100$
(c) Super-refractive conditions where $N' = -200$

3. Repeat example (7.3) for the following parameters:

$$d = 30\,\text{km}, \quad d_1 = 10\,\text{km}, \quad d_2 = 15\,\text{km}$$
$$f = 25\,\text{GHz}, \quad K_1 = 1.3, \quad K_2 = 0.6$$

4. Find diffraction loss when there is an obstacle in radio path blocking 50 % of the first Fresnel radius. If the path includes two identical obstacles, calculate the total loss.

5. A radio link operating at 7.5 GHz is required for connecting terminals T and R with a distance equal to 30 km. An obstacle (point B) is located in the radio path 10 km away the terminal T. When the above mean sea level (AMSL) of points T, R, and B is being 240 m, 500 m, and 350 m, respectively, find:

(a) Earth bulge at point B for $K = 0.67$
(b) The first Fresnel radius at B
(c) Minimum antenna centerlines for a reliable link when using similar antenna heights for 0.3 r_1 path clearance

6. A line-of-sight radiocommunications is specified with the following characteristics:

- Radio frequency: 15 GHz
- Path length: 20 km
- Antenna gain: 45 dB_i (similar TX and RX antennas)
- Feeder length: 40 m at the transmitter and 30 m at the receiver
- Feeder loss: 8 dB/100 m
- Transmitter power: 25 dB_m
- Receiver sensitivity: −74 dB_m
- Branching loss: 2.4 dB at the transmitter and 2.8 dB at the receiver
- Radiowave polarization : horizontal

Calculate the following parameters:

(a) EIRP and SG
(b) FSL, RSL, and FM

7. Consider the previous problem for a 30 km path length and 25 mm/h rain intensity; find:

(a) FSL, RSL, and FM.
(b) Rain loss for vertical polarization.
(c) Explain effects of the local climate, system capacity, and modulation type on the specified radio link characteristics.

8. Rain loss in vertical polarization for a radio link is 20 dB at 12 GHz frequency band. Find the rain loss for the same link when operating at 15 GHz with horizontal polarization.

9. Rework example (7.7) where $f = 12$ GHz , $f' = 23$ GHz, and path length is 10 km.

10. In the previous problem, find the outage time probability due to polarization discrimination without using XPIC and for $C/I_0 = 22$ dB.

11. It is required to design a radio network including 20 stations with maximum end-to-end length of 560 km and 99.8 % availability. Assuming unavailability budget as per ITU recommendations, find:

(a) Annual total outage time.
(b) Maximum acceptable errored bits per hour for STM-1.

12. Performance of a radio network is required as follows:

- Degraded minutes (DM) shall be less than 0.1 % of time where it is defined by

$$10\text{E}(-6) < \text{BER} < 10\text{E}(-3)$$

- Severely errored seconds (SES) shall be less than 0.02 % of time where it is defined by

$$\text{BER} > 10\text{E}(-3)$$

Calculate DM and SES values within the worst month for a digital network with STM-4 capacity.

13. In the previous problem, if 20 % of SES occurs continuously for greater than 1 s:

(a) Find system availability for a 500 km network (length of HRDP is 2500 km)
(b) Determine whether the specified criterion is better than HRDP or not.

14. To design a 50 km radio link in a dedicated part of your country operating at 8 GHz or 15 GHz frequency bands, find:

(a) Rain intensity for more than 0.01 % of time
(b) Rain loss special coefficient for horizontal polarization
(c) Effective length in the rain situation and related loss
(d) Rain loss for 0.005 % of time
(e) Rain loss for vertical polarization

15. Fade margin for a P-MP radio network operating at 3.5 GHz with 20 km maximum path length is 15.7 dB. To design the network in area with geoclimatic factors of $a = 0.025$ and $b = 2$, find:

(a) Outage probability due to the propagation adverse effects.
(b) Improvement in outage if the fade margin is increased by 10 dB.
(c) Repeat the case for $f = 10.5$ GHz. The maximum rain loss in the area is 2.1 dB and excess attenuation is compensated by increasing antenna gain.

16. For a 500 km LOS digital radio network of 155 Mb/s capacity, 30 % of overall unavailability budget is allocated to the propagation abnormal effects. Reference availability of 99.7 % is assumed for the 2500 km HRDP circuit. Calculate the maximum bit error rate in the worst month and total time which the network is unavailable.

17. A radio network of 1000 km length is designed as an international high-grade system for each 24-h operation; find:

(a) Total degraded minutes (DM) for which signals are received with low quality for more than 1 min per each time (BER $>$ 10E(−6))
(b) Total severely errored seconds for which there are outages (BER $>$ 10E(−3)) for more than 1 s per each time.

18. A 1000 km microwave network works as an international high-grade class; find the maximum time for which:

(a) The received signal quality is less than acceptable level, i.e., degraded minutes (one errored bit per 1,000,000 received bits in 1 min).
(b) The received signal cannot be detected, i.e., severely errored seconds (one errored bit per 1000 received bits).

19. Using Fig. 7.18 with the following assumptions,

$$\alpha = 10^\circ,\ \ \beta = 30^\circ,\ \ \Phi_A = 3\,\text{m},\ \ \Phi_D = 1.8\,\text{m},\ \ AD = 2.5 \times CD$$

All TX units and all RX units are similar and off-axis losses of antennas A and D on the overreach route are 15 dB each.

(a) In the case of standard conditions, calculate the ratio of main to overreach signals at station D.

(b) If $C/I \geq 20\,\mathrm{dB}$ is required for proper operations, determine whether the signal is detectable at station D or not.
(c) In the case of 30 and 10 dB fading on *CD* and *AD* paths, respectively, determine whether the signals are received properly at station D or not.

20. Find outage probability of a 25 km radio link within a P-MP network working at 2.5 GHz and FM = 25 dB in the following geoclimatic conditions:

(a) Dry weather in mountainous area
(b) Humid and warm weather in coastal area

21. A 40 km line-of-sight radio link operates at 8.4 GHz; find:

(a) Climate factor based on ITU-R method where $\delta N = -50$
(b) Fading occurrence probability for 500 and 800 m above mean sea level (AMSL) for TX and RX antenna centerlines

22. Find deep-fading occurrence probability in the previous problem, if 35 dB fade margin is guaranteed by proper sizing of the equipment.

23. A line-of-sight network consists of three radio links with 20, 30, and 50 km path lengths. Considering deep-fading occurrence probability of 0.02 for the 20 km link and similar geoclimatic conditions for the whole network, find:

(a) Deep-fading occurrence probability for the other two links
(b) Deep-fading occurrence probability for each link in the case of changing the equipment specifications to provide 30, 35, and 40 dB fade margins for the network links
(c) Maximum monthly outage time of the network

24. Considering 0.1 % unavailability budget for the hypothetical reference circuit, prove that network defined in the previous problem can meet the assumed availability criterion.

Chapter 8
Propagation in Guided Media

8.1 Introduction

Radiowave propagation in guided media includes the following major types:

- Atmospheric ducts
- RF cables
- RF leaky cables
- Waveguides
- Fiber optic cables

Atmospheric duct was introduced in Chap. 3 as a natural guided medium. Topics include its formation conditions, basic types, theory of propagation, ray path, minimum trapping frequency, and maximum coupling elevation angles.

RF cables are used mainly as transmission lines for connecting transmitter or receiver units to the related antennas and distributing of RF signals in VHF and UHF frequency bands. Principles of RF cable and radiowave propagation mechanism are provided in the related electromagnetic professional engineering books and documents. This chapter outlines RF leaky cable waveguides and fiber optic mechanism, modes of propagation, and related effects.

8.2 RF Leaky Cable

One of semi-guided media for radiowave propagation is RF leaky cable. This provides radiocommunications inside surrounded locations like tunnels and underground mines where communications are crucial for safety and emergency cases. As shown in Fig. 8.1, this type of RF cables is a special form of heliax cable including a number of elliptical slots uniformly arranged on the cable.

A. Ghasemi et al., *Propagation Engineering in Wireless Communications*,
DOI 10.1007/978-3-319-32783-9_8

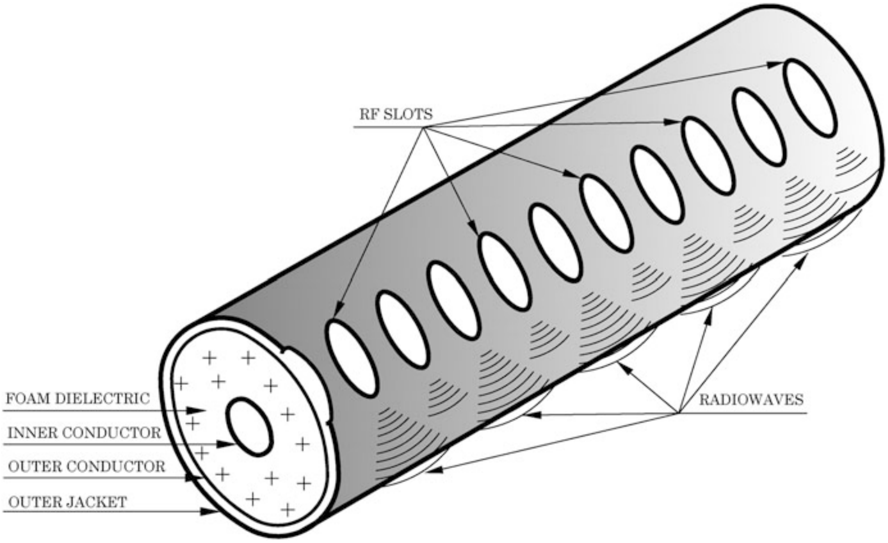


Fig. 8.1 RF leaky cable structure

When a cable is properly fed by VHF/UHF amplified radiowave signals, they will propagate inside the cable and will continuously leak from its slots which are detectable within few meters by sensitive receivers. Among a variety of limiting factors for radiowave propagation inside and outside of leaky cable, the following items are of major importance:

- Attenuation of RF leaky cable
- Coupling loss between air and RF leaky cable
- Free-space loss
- Diffraction loss
- Multipath fading

The last three items are related to the propagation of radiowaves in open area suffering some attenuation due to abnormal conditions specified in other chapters. The first two items are related to the RF leaky cable, which is explained briefly.

RF cable attenuation is usually in the order of several dB/100 m depending on its structure, material, dimension, length, and operating frequency. That is similar to normal heliax cable. Coupling loss in the air interface is considerable and usually in the range of 60–80 dB.

A typical formula for design calculations of mobile network using leaky cable is as follows:

$$\mathrm{RSL} = P_t + G_M - F_l - C_L - B_l - T_l - M_l \tag{8.1}$$

In the above formula, each parameter and its unit are:

RSL: Received signal level, in dB_m
P_t: Input signal level of leaky cable, in dB_m
G_M: Mobile antenna gain, in dB_i
F_l: Leaky cable longitudinal loss (feeder loss) in dB
C_L: Leaky cable air interface coupling loss, in dB
B_l: Body loss in dB
T_l: Train penetration loss in dB
M_l: Miscellaneous losses such as jumper cable, RF connectors, splitter, diplexer, duplexer, and RF coupler in dB

Example 8.1. An 800 m leaky cable is used to provide radio services inside a metro tunnel. RF power of 20 W at 900 MHz is fed to the cable. Find the received signal level and fade margin in the worst case for a handheld radio with the following assumptions:

$$C_L = 72\,\mathrm{dB} \ \text{ for } \ 95\,\% \text{ coverage at } 2\,\mathrm{m}$$

$$\alpha_f = 5\,\mathrm{dB}/100\,\mathrm{m}\ ,\ d = 4\,\mathrm{m}\ ,\ G_M = -2\,\mathrm{dB}_i$$

$$P_{\mathrm{th}} = -103\,\mathrm{dB}_m\ ,\ B_l = 5\,\mathrm{dB}\ ,\ M_l = 2\,\mathrm{dB}$$

$$\text{Train Penetration Loss} = T_l = 20\,\mathrm{dB}$$

Solution.

$$\begin{aligned}
P_t\,[\mathrm{dB}] &= 10\ \log\ 20 \times 10^3 = 43\,\mathrm{dB}_m \\
F_l &= \alpha_f\ \cdot\ L = 5 \times 800/100 = 40\,\mathrm{dB} \\
D_l &= \text{Distance correction factor } (2\,\mathrm{m}\ \rightarrow\ 4\,\mathrm{m}) = 3\,\mathrm{dB} \\
\mathrm{RSL} &= P_t + G_M - F_l - C_L - B_l - T_l - D_l - M_l \\
&= 43 - 2 - 40 - 72 - 20 - 5 - 3 - 2 \\
&= -101\,\mathrm{dB}_m \\
\mathrm{FM} &= \mathrm{RSL} - P_{\mathrm{th}} = -101 - (-103) = 2\,\mathrm{dB}
\end{aligned}$$

■

8.3 Waveguides

Waveguides with hollow medium surrounded by a metallic body have been employed as one of the earliest types of transmission lines to convey microwave signals. Usually, the body of waveguide is made of copper alloy with good

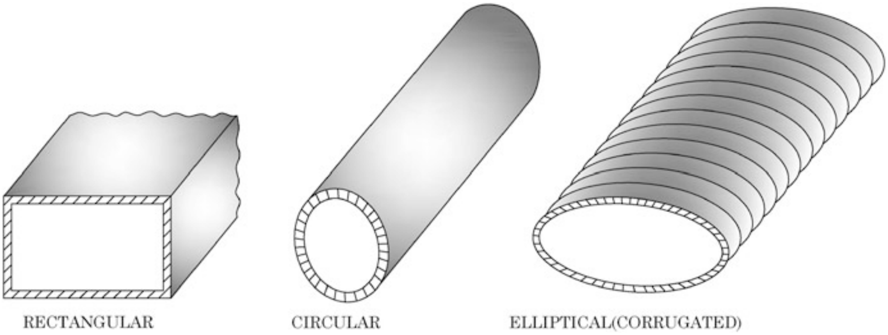


Fig. 8.2 Main types of waveguides

conductivity and sometimes golden plated. As shown in Fig. 8.2, the conventional types of waveguides are categorized based on their cross section. Major types include rectangular, circular, and elliptical shapes.

In all types of hollow waveguides, TE and TM modes, excluding TEM mode, can be propagated. For any specific mode, there is a cutoff frequency for every waveguide below which propagation is not possible. A large variety of RF components such as attenuators, couplers, isolators, detectors, circulators, and slotted lines have been developed in UHF, SHF, and EHF bands. Because of miniaturization and integration requirements in higher RF bands, instead of waveguides, many microwave RF circuitry are currently fabricated using planar transmission lines such as microstrip, stripline, and other advanced technologies.

To get field equations inside a waveguide, the wave equation is solved by applying boundary conditions. The calculation process starts with deriving related partial differential equations and solving them by the separation of variable method in suitable coordinate system, i.e., Cartesian or cylindrical, and applying boundary conditions. Detailed description and calculations are given in the books related to fields and waves.

8.3.1 TE Modes

In rectangular waveguides as depicted on Fig. 8.3, the wave equation is reduced to:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+k_c^2\right) h_z(x,y)=0 \tag{8.2}$$

Electromagnetic fields in the waveguide including E_x, E_y, H_x and H_y have sinusoidal periodic form with the following propagation constant:

$$\beta=\sqrt{k^2-k_c^2}=\sqrt{k^2-\left(\frac{m\,\pi}{a}\right)^2-\left(\frac{n\,\pi}{b}\right)^2} \tag{8.3}$$

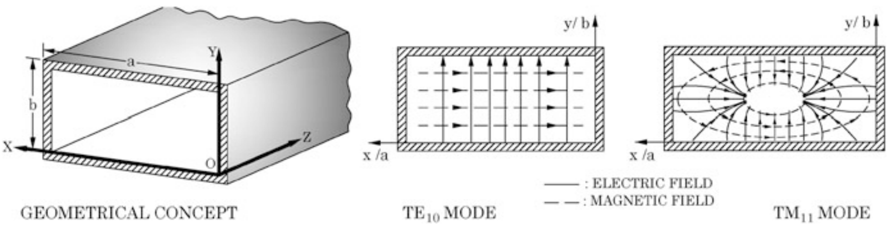


Fig. 8.3 Geometry of rectangular waveguide

where k and k_c are the operating and cutoff wave numbers, respectively. Propagation constant denoted by β is a real value corresponding to a propagation mode, when:

$$k > k_c = \sqrt{\left(\frac{m\,\pi}{a}\right)^2 + \left(\frac{n\,\pi}{b}\right)^2} \tag{8.4}$$

For each combination of m and n integers, there is a cutoff frequency $f_{c,mn}$, given by:

$$f_{c,mn} = \frac{k_c}{2\,\pi\,\sqrt{\mu\,\epsilon}} = \frac{1}{2\,\pi\,\sqrt{\mu\,\epsilon}}\,\sqrt{\left(\frac{m\,\pi}{a}\right)^2 + \left(\frac{n\,\pi}{b}\right)^2} \tag{8.5}$$

Among all available modes, the lowest cutoff frequency is called the dominant mode. For $a > b$, the lowest f_c occurs for $m = 1$ and $n = 0$, resulting in TE$_{10}$ mode with the following cutoff frequency:

$$f_{c,10} = \frac{1}{2\,a\sqrt{\mu\,\epsilon}} \tag{8.6}$$

Example 8.2. For an air-filled rectangular waveguide of $a = 2\,\text{cm}$ and $b = 1.14\,\text{cm}$, find:

1. Cutoff wave number, k_c
2. Cutoff frequency, f_c
3. How many propagation modes exist for $f_1 = 8400\,\text{MHz}$ and $f_2 = 15{,}400\,\text{MHz}$?

Solution. 1.

$$k_c = \sqrt{\left(\frac{m\pi}{2\times 10^{-2}}\right)^2 + \left(\frac{n\pi}{1.14\times 10^{-2}}\right)^2}\;, \quad m = 1\;, \quad n = 0$$

$$k_c = 50\,\pi$$

2. TE_{10} is the dominant mode and its frequency is:

$$f_c = \frac{c\times k_c}{2\pi} = 7.5\,\text{GHz}$$

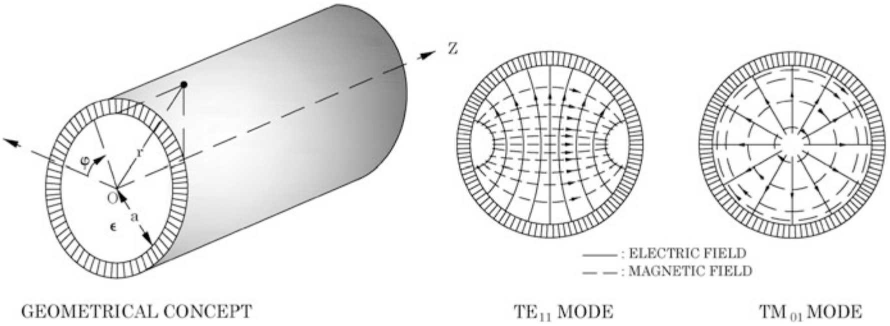


Fig. 8.4 Geometry of circular waveguide

3. Some of frequencies for TE modes are:

$$\begin{aligned} m = 0,\ \ n = 1 \ \ &\Rightarrow \ \ f_{01} = 13.159\,\text{GHz} \\ m = 1,\ \ n = 1 \ \ &\Rightarrow \ \ f_{11} = 15.143\,\text{GHz} \\ m = 2,\ \ n = 0 \ \ &\Rightarrow \ \ f_{20} = 15\,\text{GHz} \\ m = 0,\ \ n = 2 \ \ &\Rightarrow \ \ f_{02} = 26.318\,\text{GHz} \end{aligned}$$

For $f = 8400$ MHz, only TE_{10} can propagate and at $f = 15{,}400$ MHz TE_{10}, TE_{01}, TE_{11}, TE_{20} and TM_{11} can be used. ■

Also, for circular waveguides, similar approach is followed in cylindrical coordinate system (r, φ, z) as shown in Fig. 8.4 for which the wave equation is reduced to:

$$\left(\frac{\partial^2}{\partial\, r^2} + \frac{1}{r} \cdot \frac{\partial}{\partial\, r} + \frac{1}{r^2} \cdot \frac{\partial^2}{\partial\, \varphi} + K_c^2 \right) h_z\,(r, \varphi) = 0 \tag{8.7}$$

Electromagnetic fields in the waveguide are E_r, E_φ, H_r, and H_φ with the following propagation constant:

$$\beta_{nm} = \sqrt{k^2 - k_c^2} = \sqrt{k^2 - \left(\frac{\rho'_{nm}}{a} \right)^2} \tag{8.8}$$

where k and k_c are the required and cutoff wave numbers, respectively. Propagation constant denoted by β_{nm} is a real value which corresponds to propagation mode, when:

$$k > k_c = \frac{\rho'_{nm}}{a} \tag{8.9}$$

ρ'_{nm} is the mth root of $J'n$, where $J'n$ refers to the derivative of the first kind of Bessel function of the order n. Values of ρ'_{nm} are given in tables provided in the related books. The cutoff frequency is:

$$f_{c,nm} = \frac{k_c}{2\pi\sqrt{\mu\,\epsilon}} = \frac{\rho'_{nm}}{2\pi\,a\sqrt{\mu\,\epsilon}} \tag{8.10}$$

The first TE mode to propagate is the mode with the smallest ρ'_{nm}, i.e., ρ'_{11}, resulting in TE_{11} as the dominant mode in circular waveguides.

8.3.2 TM Modes

The approach to find TM modes of propagation inside rectangular waveguides is the same as finding TE modes, and similar results are concluded for β, k_c, and f_c. However, based on the obtained equations for E_x, E_y, H_x, and H_y, neither m nor n can be zero; thus, there are no TM_{00}, TM_{01}, and TM_{10} modes. The lowest order of TM waves to propagate inside the waveguide is TM_{11}, having the cutoff frequency $f_{c,11}$:

$$f_{c,11} = \frac{1}{2\pi\sqrt{\mu\,\epsilon}} \cdot \sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2} = \frac{1}{2\sqrt{\mu\,\epsilon}} \cdot \sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2} \tag{8.11}$$

which is higher than same value, $f_{c,10}$, for TE_{10}.

Also, for TM modes in circular waveguides, solving of Eq. (8.7) yields:

$$k_c = \frac{\rho_{nm}}{a} \tag{8.12}$$

$$\beta_{nm} = \sqrt{k^2 - k_c^2} = \sqrt{k^2 - \left(\frac{\rho_{nm}}{a}\right)^2} \tag{8.13}$$

$$f_{c,nm} = \frac{k_c}{2\pi\sqrt{\mu\,\epsilon}} = \frac{\rho_{nm}}{2\pi\,a\sqrt{\mu\,\epsilon}} \tag{8.14}$$

where ρ_{nm} is the mth root of $J_n(x) = 0$. Values of ρ_{nm} are given in mathematical tables provided in the related books. Based on the above formulas and ρ_{nm} values, the first TM mode to propagate is TM_{01} with $\rho_{01} = 2.405$, and TE_{11} value with $\rho'_{11} = 1.841$ is less than TM_{01}.

Example 8.3. In the case of using equal amount of copper for fabricating circular waveguide of the same length and thickness as mentioned in Example 8.2, find:

1. Cutoff frequency for the dominant mode ρ'_{11}
2. Cutoff frequency for the lowest TM mode ($\rho = 2.408$)

Solution. 1. The perimeter of the cross section of both circular and rectangular waveguides should be equal; thus:

$$2\pi r = 2(a+b) \quad \Rightarrow \quad r = 1\,\text{cm}$$

In the circular waveguide, TE_{11} is dominant mode for which:

$$f_c = \frac{\rho'_{11} \times c}{2\pi r} \quad \Rightarrow \quad f_c = 8790\,\text{MHz}$$

2. TM_{01} is the first TM mode that can be propagated:

$$f'_c = \frac{\rho_{01} \times c}{2\pi r} \quad \Rightarrow \quad f'_c = 11{,}497\,\text{MHz}$$

■

Example 8.4. By using 2.5 m of the waveguide specified in Example 8.3 as transmission line for connecting a 50 kW radar TX to a 48 dB_i rotating antenna, find:

1. Loss of power dissipated by the waveguide with 4 dB/100 m loss coefficient
2. Equivalent radiated power by the radar antenna

Solution. 1.

$$L\,[\text{dB}] = (2.5 \times 4) : 100 = 0.1\ \text{dB}$$

$$\text{TX Power Reduction Factor} = \text{Antilog}\frac{L\,[\text{dB}]}{10} = 1.0233$$

$$\text{Loss of Power} = 50000 - \frac{50000}{1.0233} = 1139\ \text{W}$$

2.

$$\begin{aligned}\text{EIRP} &= P_t + G_A - L\,[\text{dB}]\\ &= 10\ \log\ 50 + 48 - 0.1\\ &= 46.99 + 48 - 0.1\\ &= 94.89\,\text{dB}_{kw} = 124.89\,\text{dB}_w\end{aligned}$$

■

8.4 Fiber Optic Cable

8.4.1 Introduction

The idea of using light as the carrier of information had been around for many years. The first recorded attempt to modulate optical wave to carry information dates back to 1880 when Alexander Graham Bell modulated plain sunlight to transmit voice over a distance of 213 m. The photophone is usually known as the first precursor of the optical fiber. However, the problem with photophone or other FSO methods used today is the diffraction of light in a homogeneous medium, which leads to free-space loss. Although this problem might be mitigated by the employment of directional antenna, some part of energy would be lost and the system would be more vulnerable against eavesdropping.

Another category of transmission media, which fiber optics fall within, is the guided media. As shown in Fig. 8.5, in these structures, the wave is prohibited from propagating in the transverse plane and is just allowed to travel along the guiding direction. Therefore, the portion of the lost power which is referred to as free-space loss in the conventional propagation methods is ideally suppressed. Among various ideas to get the wave or the light to propagate along a specific direction and inside a specific volume, fiber optics make use of the permittivity index change between guiding medium and outer space.

In their cross sections, fiber optics typically contain a central region named "core," in which the light will propagate, and an outer region surrounding the core which is called "clad" or "cladding" by help of which the light is confined inside the core. The main approaches to implement this scenario are index-guiding and band-gap guiding.

Index-guiding of light comprises of confining light into the transmission medium using successive reflections from the interface of guiding medium with outer space. In other words, the principal guiding mechanism is total internal reflection (TIR).

On the other hand, the band-gap concept is the main agent of specular reflection at the core-clad interface. Periodic structures, such as photonic crystals, have the capability to prevent propagation of light in some specific frequencies and polarizations named band-gaps. As a result the light impinging on the interface of such a periodic structure will bounce back, as it cannot propagate inside that

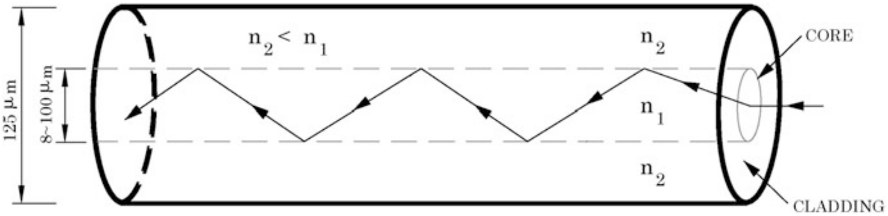


Fig. 8.5 Fiber optic concept

medium. These structures are called photonic crystals. If the clad region is filled with properly designed photonic crystal, ideally, light will be guided inside the core without leaking out.

The difference between index-guiding and band-gap guiding structures is that, in the index-guiding fiber, the clad must have lower permittivity index relative to core so that TIR condition can be met for a guided light. In band-gap guiding fiber, the clad can have higher permittivity index than the core as long as its periodic order provides a band gap for the guided light.

Nowadays, due to their unbeatable advantages, fibers are widely used. If the fiber provides just 0.01 % bandwidth at 200 THz carrier, it would be a 20 GHz channel which is huge compared to microwave counterparts. On the other hand, tiny cross section of the fibers makes it possible to bundle numerous fibers together inside cable ducts, without any problem caused by cross talk or interference.

The optical fibers essentially do not include any conducting part. Hence, there is no concern about electromagnetic compatibility and isolation. However, the fibers are sensitive to nuclear radiation, as their attenuation rises by absorbing radiation (called photo-bleaching). Also, absence of conducting parts makes it impossible to deliver electrical power through the same fiber.

8.4.2 FOC Band and Windows

8.4.2.1 FOC Band

The electromagnetic spectrum covers a wide range of frequency bands including:

- Conventional radiowaves
- Infrared, visible light, and ultraviolet
- X-rays and γ-rays

Frequency band of radiowaves as a portion of the electromagnetic spectrum was introduced in Chap. 1. The International Telecommunications Union (ITU) has set a number of regulations, recommendations, and resolutions for frequency bands up to 275 GHz. By increasing demands for more radio links and services, the radio committee of ITU has prepared several recommendations for the frequency band from 20 to 375 THz. As shown in Fig. 8.6, the band from 375 to 750 THz is visible light corresponding to 800–400 nm (8000–4000 $\overset{\circ}{\mathrm{A}}$). The higher part of infrared (IR band) including wavelengths from 20,000 to 8000 $\overset{\circ}{\mathrm{A}}$ (i.e., frequency band from 150 to 375 THz) is allocated for FOC effective communications. In this region, it is common practice to specify the band of interest in terms of wavelengths, instead of frequency as used in the radio region.

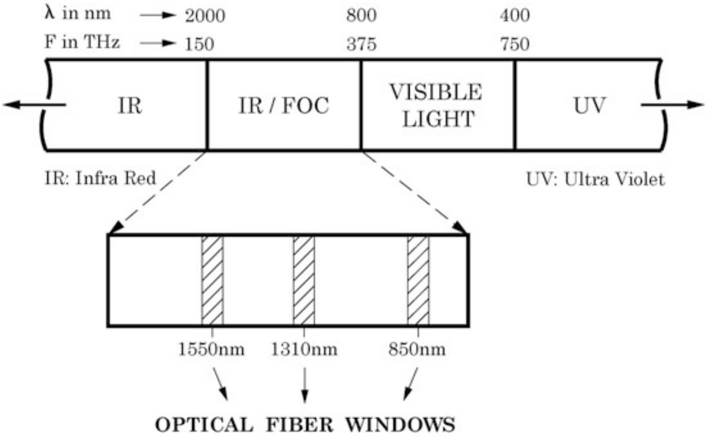


Fig. 8.6 FOC frequency band

8.4.2.2 Optical Fiber Windows

The present bandwidth for optical fiber is wavelengths from 800 to 1600 nm. This band may be expanded based on future developments. Due to the properties of material used for the fabrication of the optical fibers, the allocated bandwidth is divided into three sub-bands known as FOC windows. Attenuation, as one of the principal characteristics of FOC, is a function of wavelength. As shown in Fig. 8.7, early technologies made exclusive use of the 800–900 nm wavelength band often referred to as the first window. By improving FOC manufacturing technology, very low loss fibers were made in 1100–1600 nm region. Two windows are defined, second window centered around 1310 nm, and the third window centered around 1550 nm, which are mainly used in FOC networks. Total attenuation of the present single-mode cables employed for telecommunication is presented as a solid line in Fig. 8.7, while the dotted curve indicates their intrinsic attenuations, i.e., 0.36 and 0.15 dB/km for the first and the third windows, respectively.

While the original 850 nm band was used because of the availability of laser sources around that wavelength, longer-distance communication required operating wavelength with a lower loss in the glass fibers. The two additional bands, 1310 nm (1280–1350 nm, “second communications window”) and 1550 nm (1510–1600 nm, “third communications window”) bands, were selected considering glass fiber loss/dispersion and the availability of laser sources in those wavelengths. While the fiber loss is smallest for 1550 nm band, the dispersion of the standard glass fiber is zero at 1310 nm. A lower dispersion in the fiber allows for higher bit rates, larger channel capacities, and smaller guard bands.

Ultralow loss (ULL) fiber has been manufactured by some companies to meet the requirements of most challenging networks where very long FOC spans are required without repeaters. Maximum attenuation in some types of ULL cables at 1550 nm wavelength is as low as 0.17 dB/km which is very close to its theoretical lower bound.

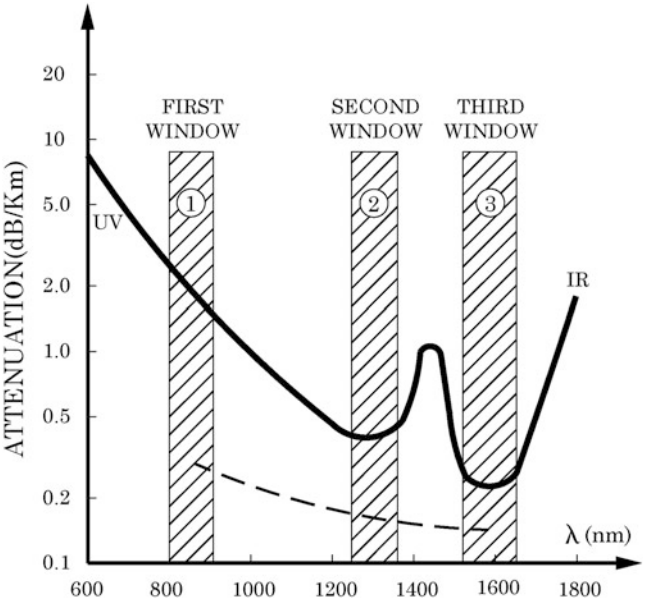


Fig. 8.7 Optical fiber attenuation vs. wavelength

8.4.3 Applications in Telecommunications

8.4.3.1 Advantages

Development of the optical fiber technology in conjunction with the advanced electronics resulted in high-speed data transmission links with some inherent advantages including the following:

1. Low transmission loss enabling to use links of long span without repeater.
2. High traffic capacity to meet ever-increasing requirements.
3. High-quality and low bit error rate communications.
4. Small-size and weight-providing flexible applications.
5. Small electric power consumption
6. Immunity to electromagnetic interference (EMI) ensuring interference-free operations in parallel links.
7. Electrical isolation, reducing cross talk, and grounding hazards.
8. Data security due to the propagation within guided media.
9. Inexpensive raw material to fabricate fiber optic cable.
10. New technologies such as wavelength division multiplexing or dense WDM, etc.

The abovementioned technical and economical reasons have made FOC link an integral part of the modern telecommunications infrastructures.

8.4.3.2 Radio Systems

As expressed earlier, one of the main applications of FOC is in the telecommunications systems as transmission media for voice, data, and image signals. To meet these requirements, in addition to FOC, there are different radio systems/links such as:

- Satellite radio links
- Microwave radio-relay networks
- VSAT and USAT systems
- Point-to-multipoint (P-MP) radio system
- UHF radio links
- Private/public mobile radio (PMR) systems
- Free-space optical (FSO) links
- Terahertz radio links
- Troposcatter systems

Using each type of radio network/link depends mainly on the hop length and required traffic capacity. Figure 8.8 determines roughly the application range of

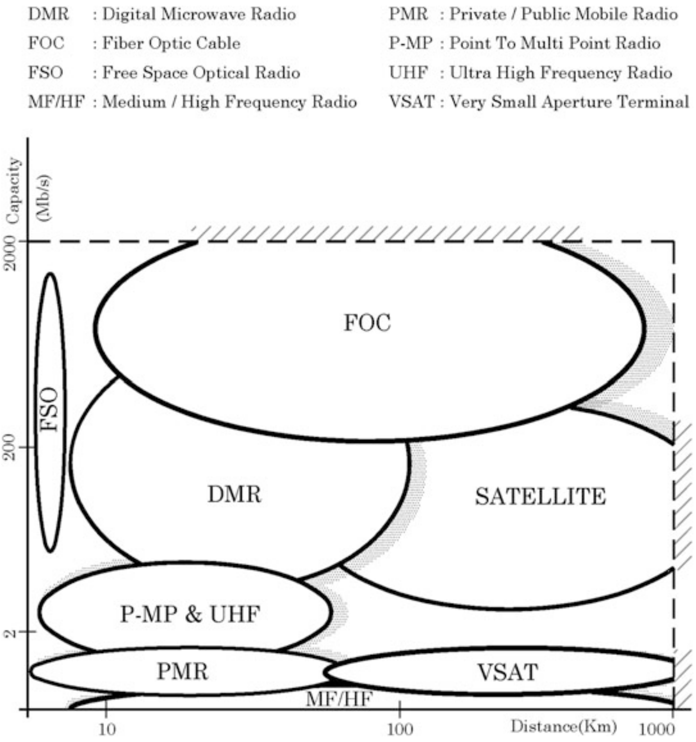


Fig. 8.8 Application chart for radio systems

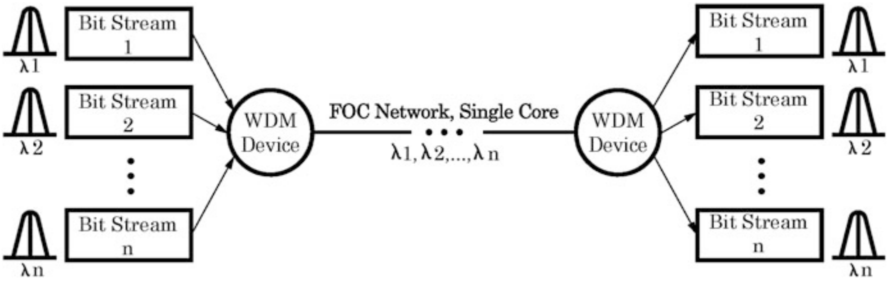


Fig. 8.9 Wavelength division multiplexing

each communication system using radiowaves. As illustrated in many cases, FOC networks are the optimized solution for such requirements.

8.4.3.3 Wavelength Division Multiplexing

Optical fibers provide much higher bandwidth compared to the high-capacity radio links. The frequency band allocated to the FOC networks corresponds to 800–1600 nm which is roughly 100 THz, enabling transporting of STM-256 to be a common practice using an FOC single channel. To meet ever-increasing requirements of modern networks, an effective approach to utilizing the wide bandwidth of optical fibers is to use wavelength division multiplexing or WDM technique. As seen in Fig. 8.9, a number of wavelengths in the fiber optic region are modulated separately and launched into a single optical fiber simultaneously.

The concept of WDM is similar to the frequency division multiplexing (FDM) in conventional multi-channel networks. As shown in Fig. 8.10, the total bandwidth is divided into a number of sub-bands each centered at a specific wavelength denoted λ_1–λ_n.

Due to linear property of FOC for low-power signals, much higher aggregated data rates can be achieved using WDM techniques. By using WDM technique, available bandwidth will be multiplied by n. In a dense wavelength division multiplexing (DWDM system), over 100 separate channels may be available through an FOC single core. Relation between $\Delta\lambda$ (bandwidth in terms of wavelength) and corresponding Δf as frequency bandwidth can be expressed by:

$$\Delta f = f_2 - f_1 = c' \times \frac{\Delta\lambda}{\lambda_1 \times \lambda_2} \tag{8.15}$$

where c' is the speed of electromagnetic waves inside FOC and all the units are in the metric system. However, for all frequencies in GHz, wavelengths in nm, and c' in km/s, it will be rearranged as follows:

$$\Delta f(\text{GHz}) = 10^3 \times c'(\text{km/s}) \times \frac{\Delta\lambda(\text{nm})}{\lambda_1 \cdot \lambda_2(\text{nm})} \tag{8.16}$$

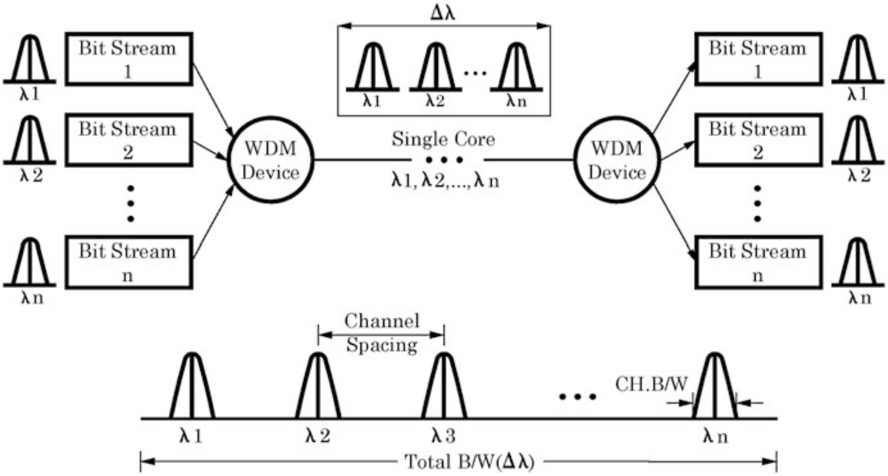


Fig. 8.10 WDM frequency spectrum

For low and medium capacity links, where $\lambda_1 \approx \lambda_2 \approx \lambda_w$, the relation (8.15) can be approximated by:

$$\Delta f = c' \times \frac{\Delta\lambda}{\lambda_w^2} \tag{8.17}$$

where λ_w is the wavelength of the related FOC window.

Example 8.5. 20 FOC channels each of 10 GHz frequency bandwidth are required to be transmitted simultaneously using single core. Considering 15 GHz as guard band between two adjacent channels, find:

1. Total bandwidth required
2. $\Delta\lambda$ assuming λ_C = 1500 nm, n_1 = 1.48 and $c = 3 \times 10^5$ km/s
3. Plot proposed WDM scheme

Solution. 1. $S = 15\,\text{GHz}\ ,\ \ \Delta F_1 = 10\,\text{GHz}\ ,\ \ n = 20$

$$\Longrightarrow \Delta F = (S + \Delta F_1) \times n = 500\,\text{GHz}$$

2. Transmission speed in the FOC is c':

$$c' = \frac{c}{n_1} = 202,702,700\,\text{m/s}$$

Using formula (8.8)–(8.17) yields:

$$\Delta\lambda = 5.55\,\text{nm}$$

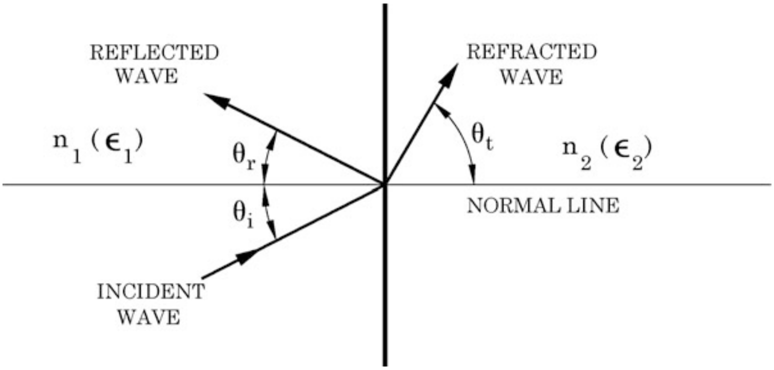


Fig. 8.11 Reflection and refraction of waves at media boundary

3. Bandwidth of each channel is:

$$\Delta\lambda_1 = \frac{\Delta\lambda}{n} \times \frac{10}{25} = 0.111\,\text{nm}$$

The proposed WDM scheme is the same as Fig. 8.10 for $n = 20$, channel $B/W=$ 0.111 nm, and channel spacing equals to 0.1665 nm. ■

8.4.4 Propagation Principles in FOC

Fiber optic cables consist of two main parts known as core and cladding with refractive indices of n_1 and n_2, respectively, where n_1 is slightly greater than n_2 $(n_2 < n_1)$.

As shown in Fig. 8.11, reflected and transmitted rays follow the Snell's law:

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1} \tag{8.18}$$

When $\theta_t = 90°$, total reflection is occurred and no ray will be transmitted to the second region. In this condition, the incident angle reaches its critical value, θ_c:

$$\frac{\sin\theta_c}{1} = \frac{n_2}{n_1} \Rightarrow \theta_c = \text{Arcsin}\left(\frac{n_2}{n_1}\right) \tag{8.19}$$

$$\cos\theta_t = \pm j\sqrt{\sin^2\theta_t - 1} \tag{8.20}$$

$$E_t = E_{ot}e^{-jk_2x} \cdot e^{\pm k_2 z \cdot \alpha} \tag{8.21}$$

In order to study propagation of radiowaves inside FOC, it is necessary to solve the wave equation. In the simplest case, the wave equation is:

$$\nabla^2 \bar{E} + k^2 \bar{E} = 0 \tag{8.22}$$

$$k^2 = \omega^2 \mu \epsilon \tag{8.23}$$

In cylindrical coordinates, Eq. (8.22) results in the following partial differential equation for the E_z component:

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial}{\partial r} + \frac{1}{r^2} \cdot \frac{\partial^2}{\partial \varphi^2} + k^2 \right) E_z(r, \varphi) = 0 \tag{8.24}$$

$$k^2 = K^2 - \beta^2 \tag{8.25}$$

Equation (8.24) can be solved by separation of variables by defining:

$$E_z = R(r) \cdot \Phi(\varphi) \tag{8.26}$$

Equations (8.24) and (8.26) yield:

$$\frac{r^2}{R} \cdot \frac{d^2R}{dr^2} + \frac{r}{R} \cdot \frac{dR}{dr} + k^2 r^2 + \frac{1}{\Phi} \cdot \frac{d^2\Phi}{d\Phi^2} = 0 \tag{8.27}$$

The part related to r should be equal to a constant value like γ^2, while φ-related component should be equal to $-\gamma^2$; thus:

$$\frac{1}{\Phi} \cdot \frac{d^2\Phi}{d\varphi^2} = -\gamma^2 \tag{8.28}$$

$$\Rightarrow \quad \Phi(\varphi) = A_1 e^{j\gamma\varphi} + B_1 e^{-j\gamma\varphi} = A_1' \sin(\gamma\varphi) + B_1' \cos(\gamma\varphi) \tag{8.29}$$

And r-related part is a Bessel differential equation as follows:

$$r^2 \cdot \frac{d^2R}{dr^2} + r \cdot \frac{dR}{dr} + (k^2 r^2 - \gamma^2) R = 0 \tag{8.30}$$

The response of (8.30) is a series known as Bessel function:

$$J_\gamma(kr) = \sum_{m=0}^{\infty} \frac{(-1)^m (\frac{kr}{2})^{\gamma+2m}}{m!(\gamma+m)!} \tag{8.31}$$

Finally it is concluded that among different cases, the following solutions are acceptable:

1. Φ is a sinusoidal function of φ in the $e^{j\gamma\varphi}$ form
2. R is a Bessel function in the $J_\gamma(kr)$ form
3. R is a modified Hankel function of the first order in the $H_\gamma^{(1)}(jkr)$ form

Considering the above assumptions, the general form of E and H fields are:

$$\text{For core,}\ r \leq a\ \Rightarrow \begin{cases} E_z = AJ_\gamma(kr)e^{j\gamma\varphi} \\ H_z = BJ_\gamma(kr)e^{j\gamma\varphi} \end{cases} \tag{8.32}$$

$$\text{For cladding,}\ r > a\ \Rightarrow \begin{cases} E_z = CH_\gamma^{(1)}(kr)e^{j\gamma\varphi} \\ H_z = DH_\gamma^{(1)}(kr)e^{j\gamma\varphi} \end{cases} \tag{8.33}$$

In Eqs. (8.32) and (8.33), A, B, C, and D coefficients shall be determined by applying boundary conditions. By evaluating the above equations, they are summarized below:

1. For $\gamma = 0$, TE and TM modes are resulted.
2. For $\gamma = 1$, hybrid modes $HE_{1\mu}$ or $EH_{1\mu}$ are resulted by solving the following equation:

$$J_1(k \cdot a) = 0 \tag{8.34}$$

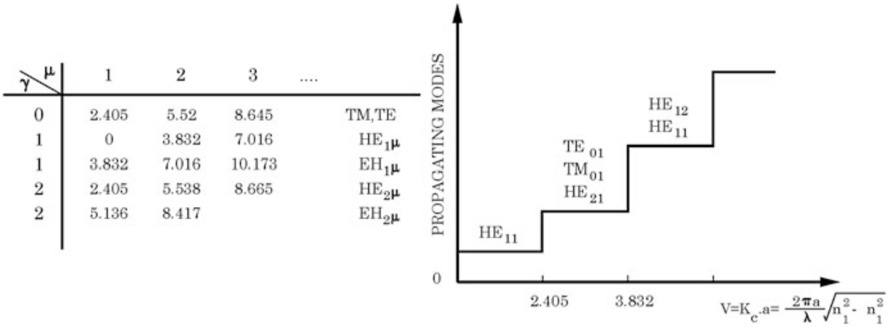
3. For $\gamma > 1$, hybrid modes of $HE_{\gamma\mu}$ or $EH_{\gamma\mu}$ forms are resulted by solving the following equation:

$$(\epsilon + 1)J_{\gamma+1}(k \cdot a) = \frac{a \cdot k}{\gamma - 1} \cdot J_\gamma(k \cdot a), (\gamma = 2, 3, \ldots) \tag{8.35}$$

Roots of Eqs. (8.34) and (8.35) are numerous in terms of γ and μ values specifying a variety of modes in the FOC. Some of V-values and corresponding modes are given in Table 8.1.

For the dielectric fiber, all modes are hybrid modes except those with $\gamma = 0$ corresponding to TE$_{0m}$ ($E_z = 0$) or TM$_{0m}$ ($H_z = 0$). When $\gamma \neq 0$, the situation is more complex and numerical methods are needed to solve Eqs. (8.34) and (8.35), for which some results are given in Table 8.1. Also, schematic patterns of the

Table 8.1 FOC propagating modes vs. normalized frequency



$\gamma \backslash \mu$	1	2	3	....	
0	2.405	5.52	8.645		TM,TE
1	0	3.832	7.016		$HE_{1\mu}$
1	3.832	7.016	10.173		$EH_{1\mu}$
2	2.405	5.538	8.665		$HE_{2\mu}$
2	5.136	8.417			$EH_{2\mu}$

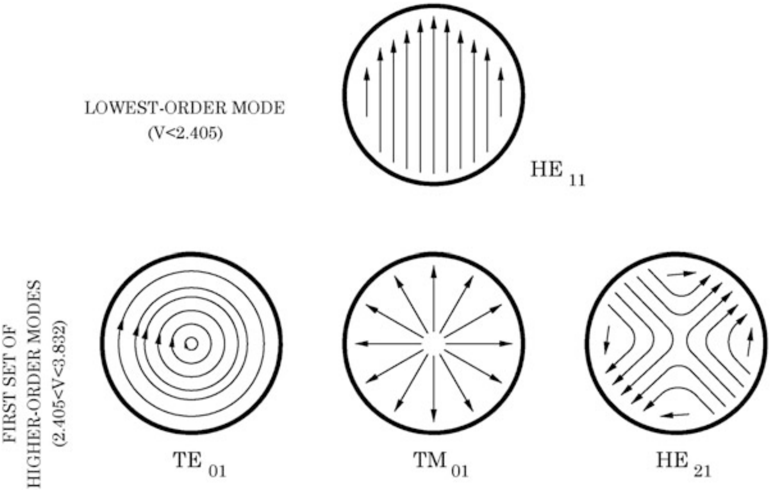


Fig. 8.12 FOC transverse electric field patterns

transverse electric field for the four lowest-order modes are shown in Fig. 8.12. When $V < 2.405$, there is a single mode known as HE_{11} which has a key role in FOC telecommunications networks.

8.4.5 Main Parameters

Some of main parameters related to fiber optic cable are defined as follows:

- **Numerical Aperture**

  Numerical aperture denoted by NA is defined by:

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2} \tag{8.36}$$

  This definition of the numerical aperture is accurate measure of acceptance angle of the fiber for rectangular waveguides and widely accepted measure for circular fibers (especially multimode fibers). In case of coupling light into a fiber, the NA indicates the range of angles within which the incident light will be coupled into the propagating mode of the fiber. Conversely, at the output end of the fiber, the NA indicates the divergence angle of the fundamental mode exiting the fiber. The higher the NA, the larger the divergence angle. The numerical aperture of standard single-mode fibers is typically between 0.1 and 0.2 for communications windows, with standard 850 nm fibers having NAs close to 0.1 and standard 1550 nm fiber having NAs close to 0.2.

- **Normalized Frequency**

  Normalized frequency called V-number is expressed by:

$$V = k_c \cdot a \tag{8.37}$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda} \cdot \text{NA} \tag{8.38}$$

  V-number is an important parameter of the fiber, as it is related to the number of propagating modes in the fiber, according to Table 8.1. While $V < 2.405$ indicated single-mode operation of the fiber, for large V-numbers, the number of modes in the fiber is roughly $V^2/2$. In the single-mode operating regime ($V < 2.405$), V-number changes monotonically with the confinement factor of the fiber, defined by the fraction of the power guided inside the core. At high V-numbers close to 2.405, the confinement factor is about 90 %. For low V-numbers and low confinement factor in a single-mode fiber, the fiber is more susceptible to bends in the fiber. For high V-numbers single-mode fiber, on the other hand, the scattering at the core-cladding interface may increase, depending on the quality of fiber fabrication.

- **Acceptance Angle**

  Acceptance angle denoted by $\theta_{\max}$, as shown in Fig. 8.13, indicates the maximum incident angle for total reflection of incident light to propagate inside FOC. It is defined by:

$$\theta_{\max} = \sin^{-1}(\text{NA}) \tag{8.39}$$

- **Relative Refractive Index**

  Relative refractive index denoted by Δ is defined as follows:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{8.40}$$

  For fiber optic cables used in the telecommunication networks, $n_1 \approx n_2$; thus, the above definition is simplified to:

$$\Delta = \frac{(n_1 - n_2)(n_1 + n_2)}{2n_1^2} \approx \frac{(n_1 - n_2) \cdot 2n_1}{2n_1^2} = \frac{n_1 - n_2}{n_1} \tag{8.41}$$

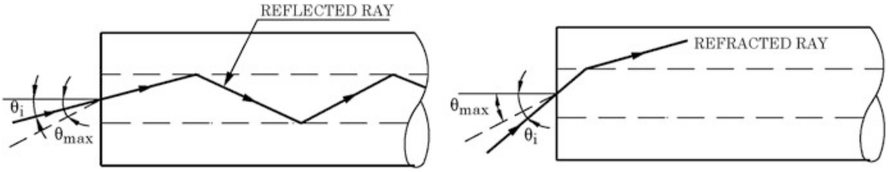


Fig. 8.13 Acceptance angle at FOC input

Finally, relation between $\varDelta$ and V is:

$$V = \frac{2\pi a}{\lambda}\sqrt{2n_1^2 \cdot \frac{n_1^2 - n_2^2}{2n_1^2}} = \frac{2\pi a}{\lambda} \cdot n_1\sqrt{2\varDelta} \tag{8.42}$$

Example 8.6. A fiber core is assumed with the following specification.
Core diameter = $a = 4\ \mu\text{m}$
Core refractive index = $n_1 = 1.48$
Cladding refractive index = $n_2 = 1.476$

1. Calculate the numerical aperture and acceptance angle.
2. Type of fiber in terms of number of modes.

Solution. 1.

$$\text{NA} = \sqrt{n_1^2 - n_2^2} = 0.1087$$

$$\theta_{\max} = \sin^{-1}(\text{NA}) = 6.24°$$

2. Normalized frequency for different windows are:

$$V = \frac{2\pi a}{\lambda} \times \text{NA}, \lambda_1 = 850\ \text{nm} \Rightarrow \quad V_1 = 3.212$$

$$\lambda_2 = 1310\ \text{nm} \Rightarrow V_2 = 2.084$$

$$\lambda_3 = 1550\ \text{nm} \Rightarrow V_3 = 1.761$$

Comparing the calculated values for V with 2.405 indicates that at $\lambda_1 = 850$ nm the cable is multimode while at $\lambda_2 = 1310$ nm and $\lambda_3 = 1550$ nm it is single-mode type. ■

8.4.6 Limiting Factors in FOC Networks

Propagation of radiowaves in FOC windows acts similar to the propagation in cylindrical optical waveguides. By traveling optical signals along the fiber, it is subject to some adverse effects which degrade the main signal. These effects can be divided into linear and nonlinear types.

8.4.6.1 Linear Effects

Two of the important challenges for the design of FOC networks including fiber optics are absorption and dispersion. Because of the exponential decay of signal with distance due to scattering or material loss (as opposed to inverse squared relation for free-space loss), it is important to reduce the loss of the fiber used in the large-scale networks.

An important loss mechanism in the fibers is the material loss. Hence, it is possible to use fibers in the wavelengths at which the silica loss is extremely low. The lowest silica absorption happens around $\lambda = 1.5\,\mu\text{m}$, i.e., S and C windows. On the other hand, zero chromatic dispersion (the dispersion related to dependence of refractive index on the wavelength in the bulk silica) occurs around $\lambda = 1.3\,\mu\text{m}$, i.e., O and E windows, in which silica has higher loss.

Practically since the total dispersion of the fiber is comprised of different contributions that may counteract each other (similar to the waveguide dispersion arising from physical geometry of the waveguide), fiber dispersion can be shifted to $\lambda = 1.5\,\mu\text{m}$ to benefit both the zero dispersion and minimum loss together.

8.4.6.2 FOC Attenuation

Attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communications network, since it plays a major role in determining the maximum length of each link. The basic attenuation mechanisms due to intrinsic and extrinsic factors are absorption, scattering, and radiative losses which can be formulated as follows:

$$\alpha = \sum \alpha_i + A \cdot \lambda^{-4} + B \tag{8.43}$$

The first term in Eq. (8.43) is related to absorption with its major causes being extrinsic absorption by impurities and intrinsic absorption by the basic constituent atoms of the fiber material. Intrinsic absorption, which sets the theoretical fundamental lowest limit for any particular material, results from the chemical properties with 0.36 dB/km for 850 nm and 0.15 dB/km for 1550 nm as typical values.

The second term in (8.43) indicates scattering losses that arise from atomic vibration variations in the material density, compositional fluctuations, and structural defects or inhomogeneous material. Scattering follows a Rayleigh λ^{-4} dependency sharply decreasing with higher wavelength.

The last term in (8.43) is related to radiative losses which occur whenever an optical fiber undergoes a bend. The radiative losses can arise from either macroscopic or microscopic bends. Macroscopic bends occur when a fiber cable turns a corner, while micro bends of the fiber axis occur due to manufacturing, cable laying, or from temperature-induced shrinking of the fiber.

8.4.6.3 FOC Dispersion

Dispersion in fiber optic cable consists of the following three main types:

- Material (chromatic) dispersion

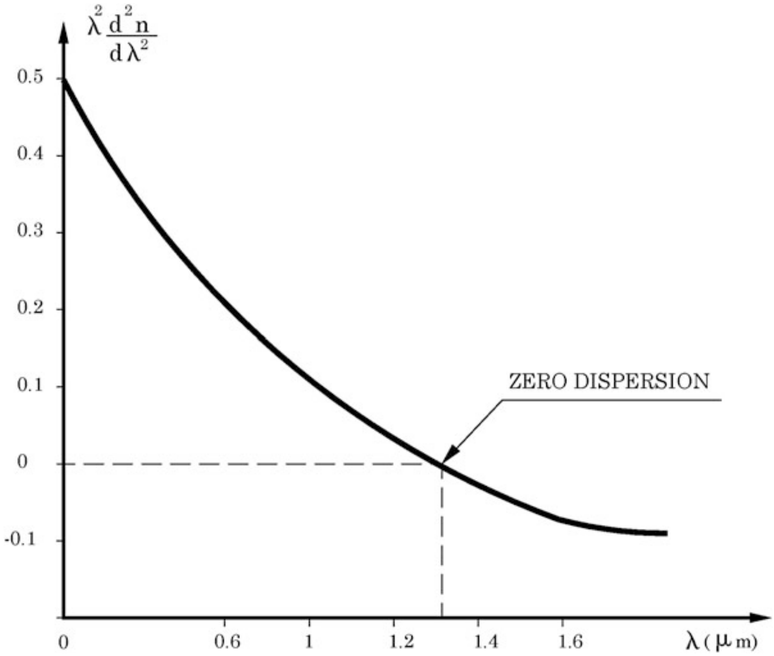


Fig. 8.14 Chromatic dispersion parameter vs. wavelength

- Waveguide dispersion
- Modal dispersion

Chromatic dispersion is due to core and cladding material having different refractive indices as functions of frequency. Time delay resulted from chromatic dispersion is expressed by:

$$\Delta\tau_C = \frac{L}{C}\left(\frac{\Delta\lambda}{\lambda}\right) \cdot \lambda_0^2\left(\frac{d^2 n_1}{d\lambda^2}\right) \tag{8.44}$$

Usually $\lambda_0^2((d^2 n_1)/(d\lambda^2))$ is given pictorially as typically indicated in Fig. 8.14. It should be noted that dispersion value is zero for a specific wave length which can be used in dispersion controlled fiber (DCF) cables.

Waveguide dispersion is related to FOC properties as a guided medium which can be expressed as follows:

$$\Delta\tau_W = \frac{L}{C} \cdot \frac{\Delta\lambda}{\lambda}(n_2 - n_1)D_W(V) \tag{8.45}$$

where $D_W(V)$ is waveguide dispersion-specific parameter. Examples of the magnitudes of chromatic and waveguide dispersion as functions of optical wavelength for a single-mode fiber optic cable are given in Fig. 8.15.

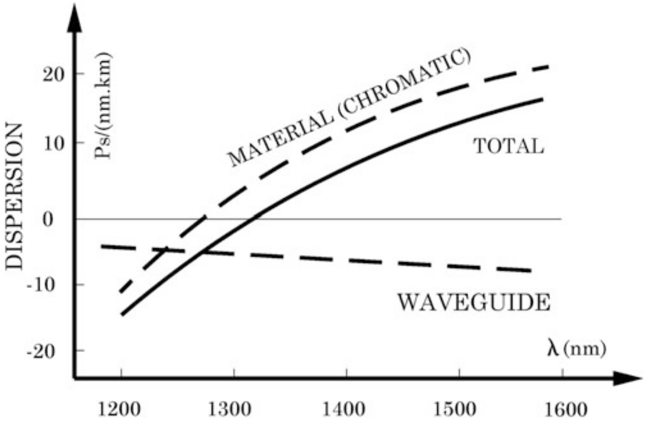


Fig. 8.15 Typical dispersion of single-mode FOC

Modal dispersion is due to using different modes of propagation inside the multimode FOC (MMF) which is expressed by:

$$\Delta\tau_{\text{mod}} = \frac{L}{C}(n_1 - n_2)\left(1 - \frac{\pi}{V}\right) \tag{8.46}$$

Time delays in (8.44)–(8.46) are in ps/nm km, and typical values for 1 km cable length are $\Delta\tau_C = 100$, $\Delta\tau_W = 3$, and $\Delta\tau_{\text{mod}} = 44{,}000$. Because of large modal dispersion, multimode fiber (MMF) cables could be used only for short distances.

8.4.6.4 Nonlinear Effects

Nonlinear effects in the propagation of optical signals in FOC-guided medium occur for high level of intensity for single-mode (SM) fibers with small cross section. Main types of nonlinear effects are:

- Self-phase modulation
- Cross-phase modulation
- Four-wave mixing (FWM)
- Stimulated Raman scattering (SRS)
- Stimulated Brillouin scattering (SBS)

Due to nonlinear processes inside an optical fiber, the signal power at a given λ is transferred to a set of longer wavelengths which are important in WDM systems because they increase cross talk between channels and limit the maximum power of each channel.

8.4.7 FOC Standards

Standards are an essential component of any telecommunications system. In FOC networks, standards define the minimum specifications and performance requirements, enabling different FOC networks to work and communicate satisfactorily.

We introduced main standards in telecommunications field in Chap. 1. For FOC networks, major standard agencies include ITU-T, IEC, ISO, IEEE, and TIA. These standards cover a wide range of applications such as components, devices, measurements and test procedures, safety, reliability, performance, and networking.

Optical fiber cables are mainly introduced by ITU-T recommendation Nos. G.651–G.657. The G.651 defines the graded index multimode fiber with core and cladding diameters of 50 μm and 125 μm respectively. Its attenuation is around 4 dB/km at FOC first window 850 nm and around 2 dB/km at 1310 FOC second window (λ=1310 nm)

The most commonly used non-dispersion-shifted single-mode fiber (SMF) is defined by G.652 for using in 1310 and 1550 nm wavelengths. SMF cables are classified in four categories designated as A, B, C, and D with zero dispersion.

8.4.8 FOC Telecom Networks

Features and advantages of the optical fiber cables make them a versatile means for a variety of applications. The largest customer for FOC is telecommunications network where large streams of voice, video, and data can be transported by fibers.

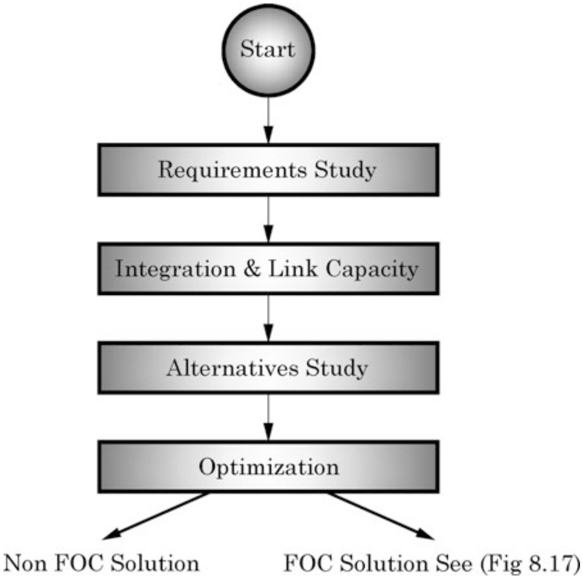
8.4.8.1 System Selection

To design a telecommunications network, some preliminary studies shall be done and crucial decisions shall be taken. Main steps are given in Fig. 8.16. For each step, many items should be considered based on the designer's experience, available technologies, equipment, and facilities.

In case of selecting FOC network as the optimized solution, then the steps shown in Fig. 8.17 should be followed.

By launching optical signal into a fiber cable, it will be attenuated and distorted continuously along the cable due to scattering, absorption, and dispersion mechanisms. These adverse phenomena will limit the maximum length of optical fiber cable for effective communications.

Fig. 8.16 Main steps for telecom system selection



8.4.8.2 FOC Basic Links

Each telecommunications network, based on its size, has a number of service points or nodes including terminals, repeaters, drop repeaters, and junctions. The network topology is in a manner by which the nodes are connected together. There are some basic topologies each characterized by its own features, advantages, and limitations, in terms of cost, reliability, outage, performance, and expandability.

As shown in Fig. 8.18, basic topologies for telecommunications networks are:

- Bus topology
- Star topology
- Ring topology
- Mesh topology

8.4.8.3 FOC Diversity Techniques

To improve the reliability of FOC media in telecommunications networks, different types of diversity techniques may be used. Main diversity methods are shown in Fig. 8.19 and are known as:

- *Wavelength Diversity* by WDM technology using different wavelengths within the same core.
- *Core Diversity* by using different cores in the same cable
- *Cable Diversity* by using different cores and cables in the same trench (route)
- *Route Diversity* by using different cores, cables, and trenches (routes)

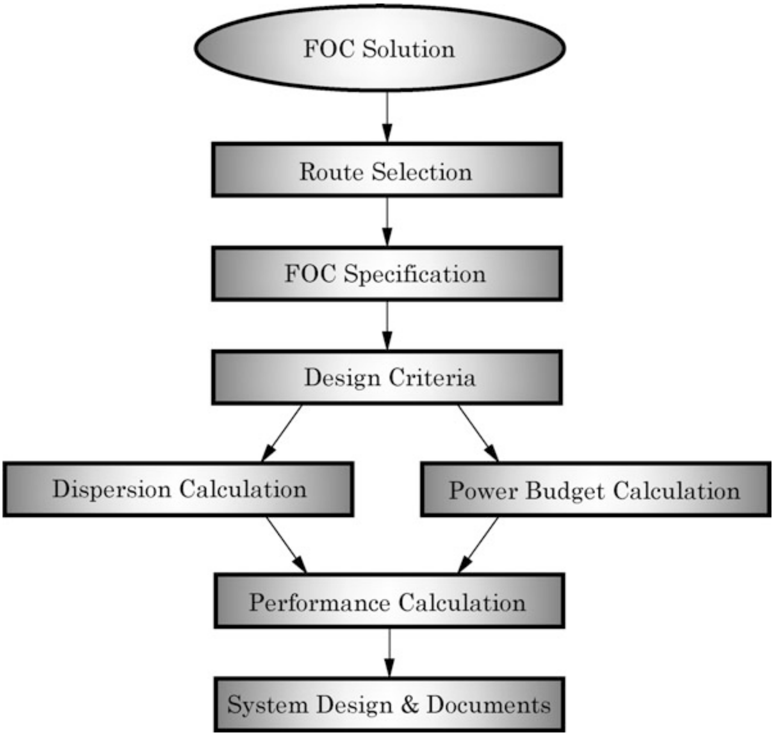


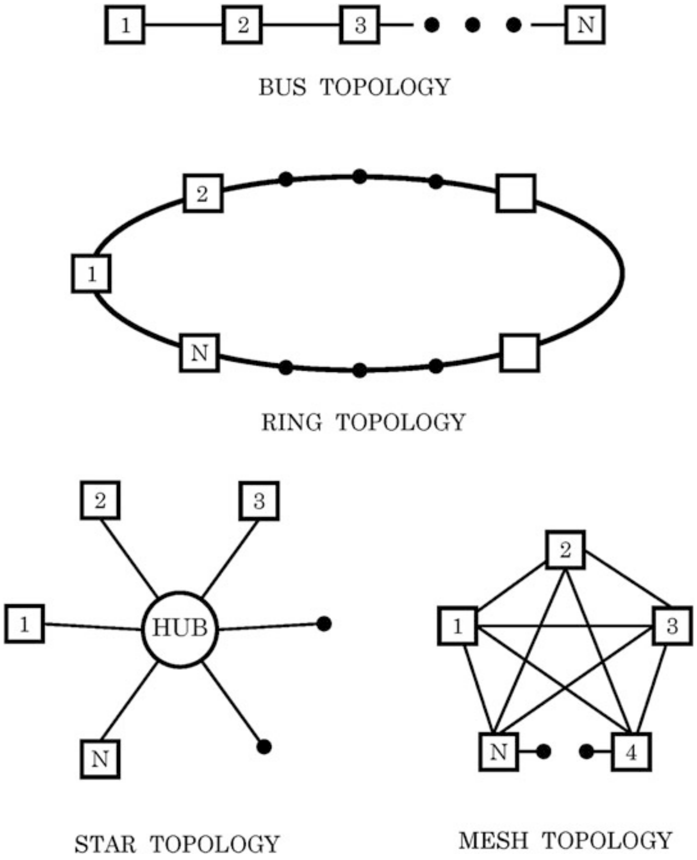
Fig. 8.17 Main steps for FOC network design

Example 8.7. A telecommunication network in (1 + 1) configuration should be designed for connecting six nodes as in Fig. 8.20, determine:

1. Competent solution for handling STM-64 signals.
2. Network topology and diversity technique that can be employed in case of using a 24-core fiber cable.
3. Suitable alternatives if we limit the traffic at 100 Mb/s for emergency cases only.

Solution. 1. Total capacity is $64 \times 156\,\text{Mb/s} \sim 10\,\text{Gb/s}$; according to the system application chart (Fig. 8.8) considering distances and system capacity, the competent solution is FOC technology.

2. By using 24-core cable, the best topology is ring type and core diversity by using core Nos. 1–4 for "go channels" and core Nos. 5–8 for "return channels".
3. In addition to FOC, suitable alternatives for 100 Mb/s traffic are satellite communications and microwave terrestrial networks. ■


BUS TOPOLOGY

RING TOPOLOGY

STAR TOPOLOGY

MESH TOPOLOGY

Fig. 8.18 Basic topologies of FOC networks

8.4.9 FOC Link Calculations

8.4.9.1 Objectives

For FOC links up to STM-64 (10 Gb/s), linear effects of propagation media including attenuations and dispersions are paramount issues for the link power budget calculations. However, in FOC link including bit rates more than 10 Gb/s, long distances using optical amplification, and WDM, nonlinear effects change the situation deeply.

We explain the link power calculations based on linear effects in this chapter. For a given set of a FOC link components and fixed design criteria, power analysis must be applied to determine whether the FOC link meets the requirements. The purpose of technical calculations for system planning is to ensure that:

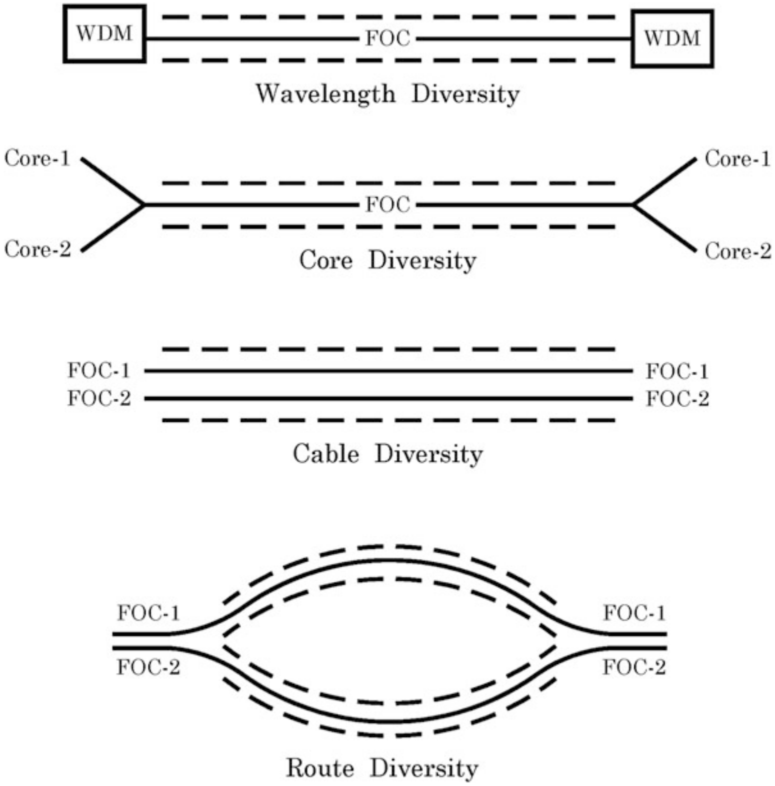


Fig. 8.19 FOC diversity techniques

- The received signal level at the receiver input is adequate.
- The link bandwidth is enough to handle the required traffic.
- The required system quality and performance are satisfied.

8.4.9.2 Terms and Definition

To avoid misleading in technical calculations of FOC system planning, it is necessary to define the related terms accurately:

- *Receiver Sensitivity* or threshold is the minimum signal level (power) in dB_m at its input that could be detected properly. This value is a function of the bandwidth and required quality in terms of bit error rate.

  The receiver sensitivity is given by manufacturer for his products or typically can be determined using relevant graphs such as shown in Fig. 8.21 for receiver with 622 Mb/s (STM-4) capacity.

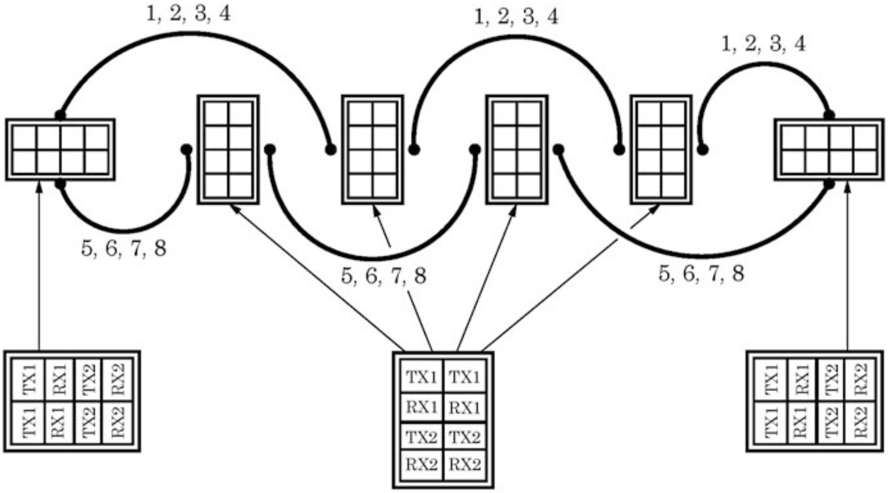


Fig. 8.20 System configuration for Example 8.7

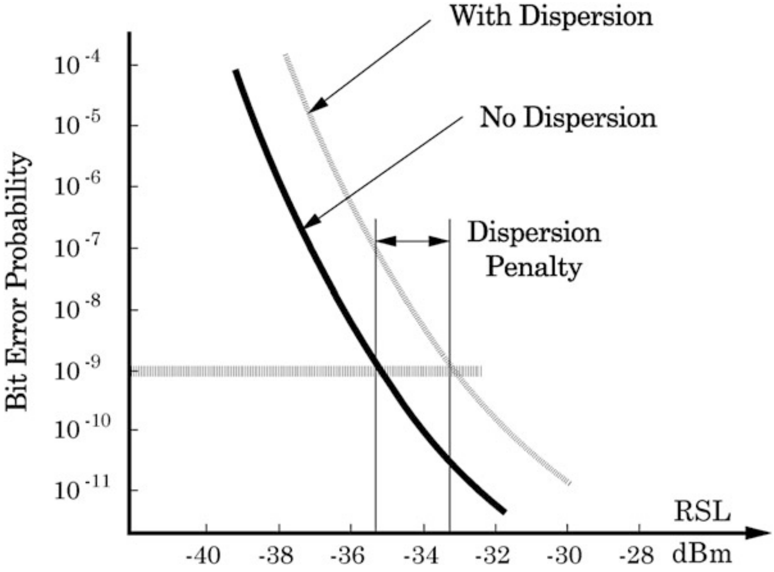


Fig. 8.21 Bit error probability

- *Power Budget* or system gain (SG) is power difference between transmitter (TX) output and receiver (RX) input at the worst case, i.e., minimum of the TX output power and maximum of the RX input power.

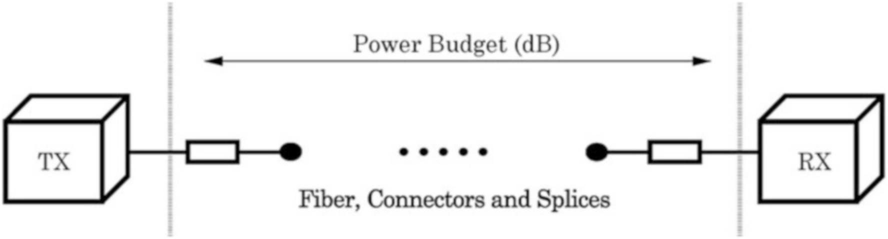


Fig. 8.22 Power budget concept

Power budget concept is shown pictorially by Fig. 8.22. As an example, for TX output power 1–2 dB_m and RX sensitivity -23 to $-30\,\mathrm{dB}_m$, then:

$$SG = 1 - (-28) = 29\,\mathrm{dB}_m$$

- *Power Margin* for a link is the difference in dB, between the actual received power level and the minimum required power which is normally considered at the design stage for a number of reasons such as:
  - Aging of devices used in FOC link.
  - To cater for potential splices in future due to repair or expansion purposes.
  - Excess fiber loss in case of future rerouting.
  - Future expansion of system capacity, if required.
- *Attenuation* is referred to all losses in dB including:
  - Fiber core loss
  - Connector loss
  - FOC splice loss
- *Power Penalties* are defined as the increase of RX input power required to compensate undesired effects of IR wave propagation within an FOC-guided medium, such as:
  - Dispersion
  - Reflection in FOC interfaces
  - Cross talk in couplers
  - Modal noise and dispersion
  - Polarization sensitivity

Among the above factors, chromatic dispersion as a linear phenomenon in FOC links using single-mode fibers has great impact on typical calculations. However, other types of power penalties should be taken into account for high-capacity systems (more than STM-64) or links based on WDM technology.

- *Intrinsic Losses* for fibers refer to the imperfection in the atomic structure of the fiber material due to missing molecules or the presence of oxygen defects. In case of using pure material for the fabrication of optical fibers, all assimilations would be intrinsic.

  Also, when two fibers are connected by splices or connectors, intrinsic losses occur due to mismatching of core area, core diameter, and numerical aperture.
- *Extrinsic Losses* for fibers refers to impurities and imperfection of the added material to the fiber during its fabrication. These materials such as iron, nickel, and chromium and hydroxyl ions change energy level of the electrons. For example, the presence of hydroxyl ions (–OH) results in a peak at 1383 nm wavelength in the absorption spectrum of the fiber, commonly known as water-peak.

  Also, extrinsic losses may exist when connecting two fibers. The extrinsic losses can be because of the lateral, angular, and longitudinal displacements or separations of the fiber cores.

8.4.9.3 Dispersion Penalty

A typical dispersion penalty as a function of the dispersion at the RX input is shown in Fig. 8.23. For a given BER, say 10^{-9}, the minimum RX input level should be minus 33 dB_m including dispersion and minus 35 dB_m when there is no dispersion.

Dispersion penalty is the increase in the received signal level in dB_m to eliminate the degradation of BER due to the fiber dispersion. Thus, for the mentioned example:

$$P_d = -33 - (-35) = 2\,\mathrm{dB}_m$$

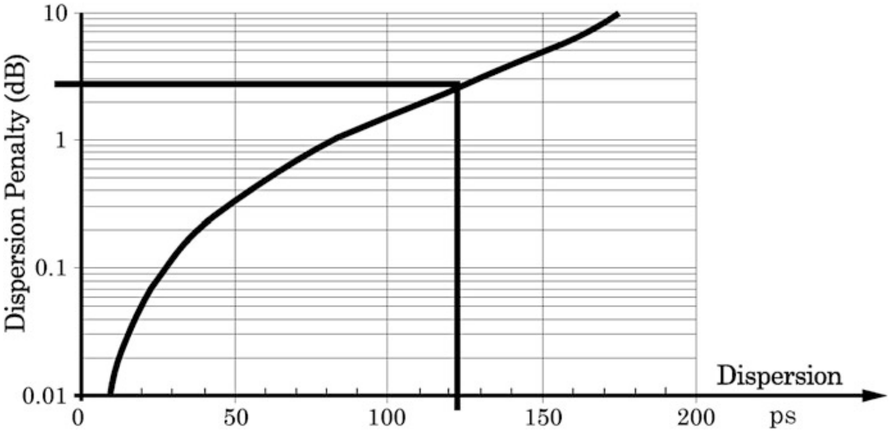


Fig. 8.23 Dispersion penalty

The following points should be taken into account when dispersion penalty is considered in the link power budget calculations:

- Typical value for BER is 10^{-9}
- Typical value for dispersion penalty is 1.5–2 dB
- Several analytic methods can be used for calculation of P_d. One of them is expressed by the following formula

$$P_d\ [\text{dB}] = -10\log[1-(\pi BD_t)^2/2] \tag{8.47}$$

where B is bit rate in b/s and D_t is the total dispersion in ps (picosecond).

- In FOC links not using WDM technique or high-speed bit streams, D_t is limited to the chromatic dispersion that can be expressed by:

$$D_t = D_c \times S \times L \tag{8.48}$$

where:
D_c is the fiber dispersion coefficient in ps/nm km
S is the spectral width of TX in nm
L is the length of the link in km

For exact planning, the dispersion penalty specific to the standard bit streams has been prepared as given typically in Figs. 8.24 and 8.25 for STM-1 to STM-64, respectively.

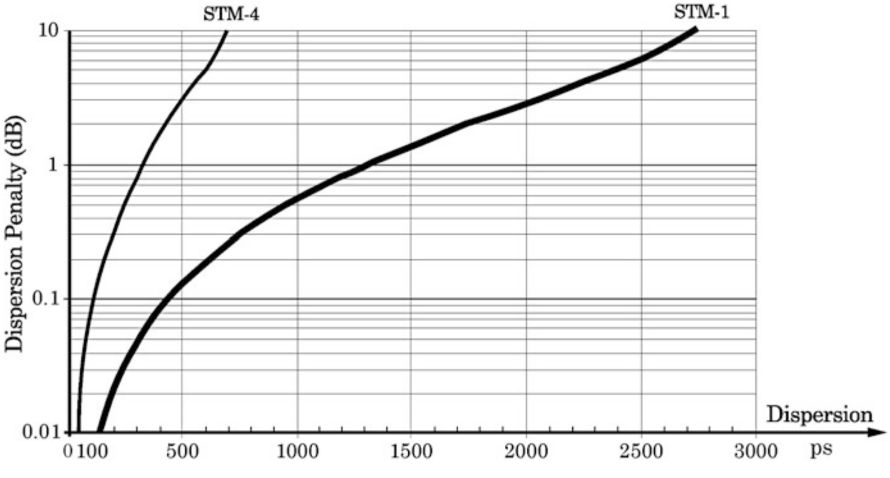


Fig. 8.24 Dispersion penalty for STM-1 and STM-16

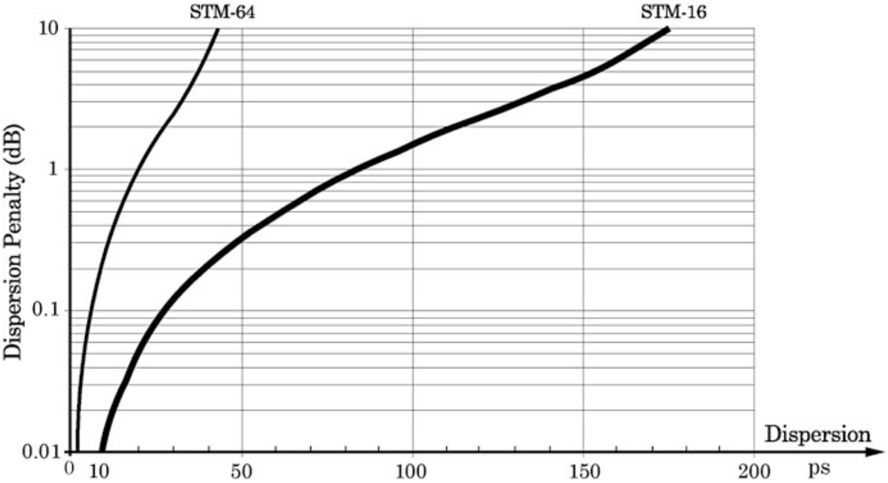


Fig. 8.25 Dispersion penalty for STM-16 and STM-64

Example 8.8. An FOC link with 60 km length uses single-mode fiber in 1550 nm wavelength, TX spectral width of 0.1 nm, α_c = 0.25 dB/km, and dispersion coefficient of 18 ps/nm km; find:

1. FOC absorption loss and dispersion.
2. System gain if RX with $-28\,\text{dB}_m$ sensitivity and TX with $+2\,\text{dB}_m$ output are used.
3. Assume 7 dB for all other losses and 2 dB of dispersion penalty, then calculate the link power margin.

Solution. 1.

$$L_c = L \times \alpha_c = 60 \times 0.25 = 15\,\text{dB}$$
$$D_t = 18 \times 0.1 \times 60 = 108\,\text{ps}$$

2.

$$S_G = P_t - P_r = +2 - (-28) = 30\,\text{dB}_m$$

3.

$$P_m = S_G - L_c - P_d - L_m$$
$$P_m = 30 - 15 - 2 - 7 = 6\,\text{dB}$$

■

8.4.9.4 Link Power Budget

Link power budget calculation is an equation between all gains and losses components involved in each FOC link. Power budget calculations can produce a variety of results depending on the designer needs. General form of the link power budget equation is:

$$\mathrm{SG} = P_b = \Sigma L + \Sigma P + P_m \tag{8.49}$$

$$\mathrm{SG} = P_t - P_r \tag{8.50}$$

$$\Sigma L = L_f + L_c + L_i + L_e + L_s \tag{8.51}$$

$$\Sigma P = P_d + P_n \tag{8.52}$$

The above notations are referred to the factors indicated below where:

SG [dB$_m$]: System gain or power budget
P_t [dB$_m$]: TX output power
P_r [dB$_m$]: RX input sensitivity
L_f [dB]: Fiber core attenuation
L_c [dB]: Connectors loss
L_i [dB]: Cable intrinsic loss
L_e [dB]: Cable extrinsic loss
L_s [dB]: Core splice loss
P_m [dB]: Power margin
ΣP: Sum of penalties
ΣL: Sum of losses
P_d [dB]: Dispersion penalty
P_n [dB]: Nonlinear penalties

Based on link-specific conditions, some additional losses or penalties such as extrinsic items can be added.

Example 8.9. Using data given in Example 8.8, find:

1. Lifetime of the FOC link if there is on average one cable break per year and 0.05 dB loss for each fusion splice.
2. How much the power margin will be increased by using ultralow loss cable with 0.17 dB/km loss factor?
3. Study the case to relocate one of terminals in new location with 20 km new cabling after 12 years.

Solution. 1. Considering 60 % of the link power margin for the future splicing, then:

Maximum acceptable splicing loss = $6 \times 0.6 = 3.6$ dB
Total no. of future splices = 3.6 : 0.05 = 72

For each cable break, two fusion splices are needed; thus, total lifetime will be:

$$L/T = 72 : 2 = 36\,\text{years}$$

2.

$$L_f^{'} = \alpha_c^{'} \times L = 0.17 \times 60 = 10.2\ \text{dB}$$

$$\text{thus,}\ \ P_m^{'} = P_m + (L_f - L_f^{'}) = 10.8\ \text{dB}$$

(minor: the example asked for the increase in Pm.)

3. After 12 years, there will be 12 cable break which will cause an additional loss equal to $12 \times 2 \times 0.05 = 1.2\,\text{dB}$. Assuming totally 10 splice for new cabling, this will impose $10 \times 0.05 = 0.5\,\text{dB}$ loss. Also, by using similar fiber, i.e., 0.25 dB/km loss, fiber attenuation will increase by $20 \times 0.25 = 5\,\text{dB}$, and then the total loss increase will be:

$$E_L = 1.2 + 0.5 + 5 = 6.7\ \text{dB}$$

This amount of excess loss is more than the maximum available power margin (6 dB). Therefore in new cabling ultralow loss (ULL) fiber shall be used. In this case after 12 years, available power margin will be:

$$\begin{aligned} P_m^{'} &= S_G - L_c - L_c^{'} - P_d^{'} - L_m^{'} \\ &= 30 - 15 - 0.17 \times 20 - 2 - (7 + 10 \times 0.05) \\ &= 2.1\,\text{dB} \end{aligned}$$

■

8.4.9.5 Optimized FOC Link Planning

According to the basic descriptions and definitions presented, the following steps shall be taken for a professional FOC link planning:

- **Step 1:** Determine tentative equipment and material specifications and data.
- **Step 2:** Apply design criteria and typical values for the selected system capacity, quality, and allowance for future modifications.
- **Step 3:** Evaluate all related losses and penalties.
- **Step 4:** Apply link power calculation formula and find power margin.
- **Step 5:** Prepare initial calculation sheet and evaluate the results for final computer-aided design. The optimized solution should be selected based on the project-specific conditions, material availability, costs, and operational and technical considerations.

Example 8.10. A 70 km FOC link should be established for handling of STM-64 signals, including the following assumptions:

$$\lambda_c = 1550\,\text{nm}, \quad \alpha_c = 0.25\,\text{dB/km}$$

$$S = 0.1\,\text{nm}, \quad D_c = 17\,\text{ps/nm km}$$

1. Find maximum fiber absorption and dispersion.
2. Considering 5 dB penalty for dispersion, determine the maximum allowed dispersion.
3. What is your suggestion to alleviate the excess amount of dispersion?

Solution. 1.

$$L_f = \alpha_c \cdot L = 0.25 \times 70 = 17.5\,\text{dB}$$

$$D_t = D_c \cdot S \cdot L \implies D_t = 17 \times 0.1 \times 70 = 119\,\text{ps}$$

2. Using Fig. 8.25, for STM-64, 5 dB dispersion penalty can compensate up to 38 ps dispersion.
3. To alleviate excess dispersion, low dispersion optical fiber or dispersion compensation module (DCM unit) should be used considering the relevant link parameters. ■

8.4.10 Mechanical and Civil Considerations

To complete an FOC link design, in addition to the above estimations and calculations, it is necessary to study mechanical and civil requirements including the following items:

- Cable route surveying
- Cable route selection
- Cable trench details
- Manhole requirements and details
- Selection of cable type such as aerial, OPGW, in-duct, in-trench, subsea, etc.
- Outer jackets and special protections
- Site-specific health, safety, and environment (HSE) requirements
- Mechanical reinforcement considerations for especial locations such as road crossing, in tunnels, over slopes, etc.
- Practical consideration for cable laying
- Cable route indicators and markers
- Grounding network requirements
- AC and DC mains electrical power

8.5 Summary

The following issues were explained regarding the radiowave propagation in the guided media:

- RF leaky cable for radiocommunications inside surrounded areas such as tunnels and mines.
- Rectangular and circular waveguides for connecting radio units to the antennas including TE and TM modes of propagation and related cutoff frequency.
- Principles of propagation within FOC were introduced for solving the wave equation and extracting hybrid modes.
- Definition and formulas of the FOC main parameters including numerical aperture, normalized frequency, acceptance angle, and relative refraction index.
- FOC frequency band and efficient windows were introduced.
- Advantages of FOC in telecommunications were explained in terms of technical, economical, and operational aspects.
- A brief description of WDM technology was given.
- Limiting factors in the application of fiber cable in the telecommunication networks including attenuation, dispersion of different types, and nonlinear effects were defined and some useful formulas were introduced.
- Reference made to the major standards related to the fiber optic technology.
- Main steps for system selection, basic types of FOC links, topology, and diversity techniques were explained.
- Various parameters related to the FOC link calculations including RX sensitivity, power budget, power margin, attenuation, power penalties, dispersion, and intrinsic and extrinsic losses were defined and explained.
- Link power budget calculation is presented by solving examples.
- Classification of steps required for an optimized solution is presented.

8.6 Exercises

Question

1. Specify difference between radiowave propagation in free-space and guided media.
2. Specify normal distance and frequency ranges of radiowaves in leaky cables used in tunnels and mines.
3. Define air interface coupling loss and give its rough value in RF leaky cables.
4. Explain why TEM mode cannot propagate in the waveguides.
5. Define cutoff, dominant mode, and operating frequencies in the waveguides.
6. What is the practical range of attenuation in commercial waveguides?
7. Define main parameters for fiber optic cables.

8. With reference to Fig. 8.6, determine:

   a. Frequency and wavelength ranges allocated to FOC.
   b. What are main advantages of the allocated windows for FOC communications?

9. Explain four main reasons for using of FOC in telecommunications.
10. With reference to the application chart of radio systems (Fig. 8.8), determine competent alternatives for:

    a. 2 Mb/s traffic and 500 km hop distance.
    b. 200 Mb/s traffic and 200 km hop distance.

11. What is the main concept and application of WDM and DWDM technologies? Give practical examples for them.
12. Explain major standard agencies for FOC technology.
13. Explain the nature of intrinsic and extrinsic losses in FOC links
14. What are the main types of FOC network topology and their advantages and applications?
15. What is the main purpose of using diversity techniques in FOC links? Specify main types of these links.
16. What are the objectives of FOC link calculations?
17. Define power margin in an FOC link and specify the reasons for considering it.
18. Define power penalties and specify its sources.
19. Define dispersion, kinds, and countermeasures in FOC links.
20. What steps should be taken for the optimized planning of an FOC network?

Problems

1. TX output power of 30 W is fed to leaky cables of 300 and 500 m lengths via a splitter with 4 dB loss. Find the received signal level and fade margin in the worst condition for handheld radio unit with the following assumptions:
$C_l = 69\,\text{dB}$ for $95\,\%$ Coverage
$\alpha_f = 4\,\text{dB}/100\,\text{m},\ G_r = -3\,\text{dB}_i,\ R_{\text{th}} = -103\,\text{dB}_m$
$B_l = 3\,\text{dB},\ M_l = 2\,\text{dB},\ T_l = 18\,\text{dB}$

2. An air-field rectangular waveguide of $a = 7.2$ cm and $b = 3.1$ cm dimensions is used as a transmission line for connecting of radio unit to the related antenna. What kind of modes can be used for $f_1 = 3$ GHz and $f_2 = 6$ GHz?

3. An air-field rectangular waveguide is required for handling radar waves between antenna and radar input/output. The desired operating frequency in the dominant mode is 20 % higher than cutoff frequency and 25 % less than cutoff frequency of next higher-order mode. Assume $a = 3$ cm and $f = 3000$ MHz. Find the lowest value for b.

4. Repeat Example 8.3 for data given in Problem 2.

5. An air- field circular waveguide is used to connect of 30 dB_m TX output power to a parabolic antenna of 44 dB_i gain. For 40 m length of waveguide and attenuation coefficient 5 dB/100 m, find:

a. Equivalent isotropic radiated power (EIRP) of the antenna in the direction of its main axis.
b. Length of transmission line that 25 % of TX power will be dissipated.

6. An air-filled circular waveguide is used to pass a 7.5 GHz radiowave.

1. Calculate the inside diameter of the waveguide such that its lowest cutoff frequency is 25 % below the operating RF frequency.
2. What modes can be propagated at 10 GHz RF frequency?

7. Solve Example 8.5 for a DWDM system including 80 FOC channels each of STM-16 capacity with 10 GHz bandwidth and 12 GHz as guard band.

8. Solve Example 8.6 for $n_1 = 1.5$, $n_2 = 1.495$, and $a = 5\ \mu\text{m}$.

9. Repeat Problem 8 for $n_1 = 1.48$, $n_2 = 1.47$, and $a = 3\ \mu\text{m}$.

10. With reference to Fig. 8.8, determine the competent system to meet the following requirements:

1. 2 Mb/s traffic and 500 km hop distance
2. 200 Mb/s traffic and 5 km hop distance
3. 400 Mb/s traffic and 300 km hop distance

11. An FOC network in (1 + 1) configuration is shown in Fig. 8.26, determine:

1. Network topology
2. Type of diversity
3. What changes should be made in Fig. 8.26 for (2 + 1) configuration

12. Solve Example 8.8 with the following changes:

$$L = 50\,\text{km},\ \ P_{\text{th}} = -27\,\text{dB}_m,\ \ P_t = 1\,\text{dB}_m,\ \ P_d = 3\,\text{dB}$$

13. There is 5 dB power margin for a 60 km FOC link operating at $\lambda_c = 1550$ nm with fiber loss factor of 0.25 dB/km, find:

1. Lifetime of the FOC link considering one cable break per year and 0.06 dB loss for each fusion splice.
2. How much the power margin will be increased by using ultralow loss cable with 0.17 dB/km loss factor?
3. Study the case and explain your comments for relocating one of terminals with 25 km new cabling after 10 years.

14. Refer to Fig. 8.21 and specify the minimum RX input to detect received signal of STM-4 with BER$< 10^{-9}$.

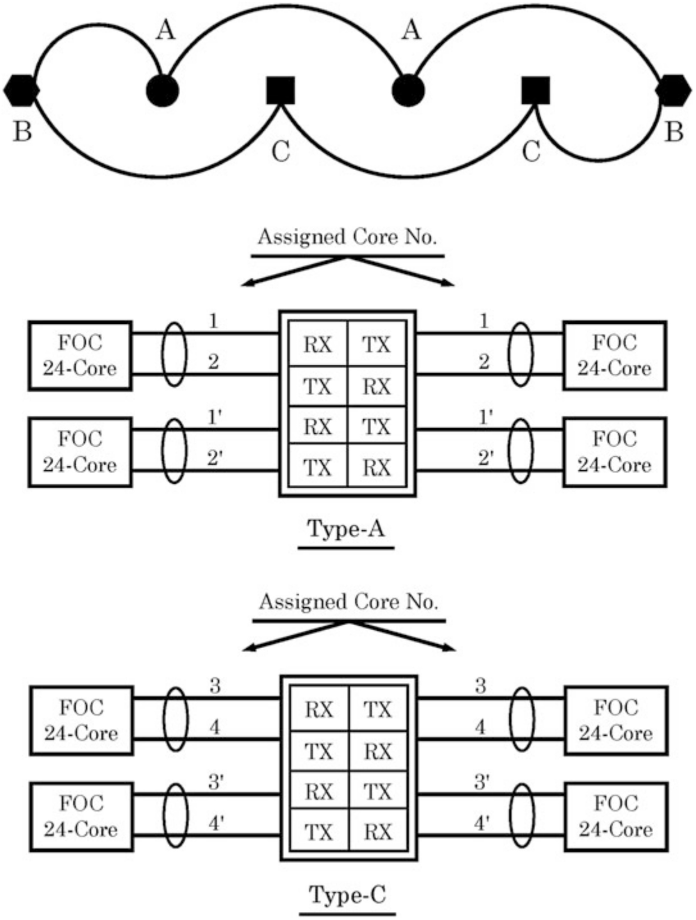


Fig. 8.26 FOC network for Example 8.10

15. A new STM-64 link should be established by using spare cores of an existing 80 km FOC link operating at STM-16. The present power margin is 6 dB in the worst condition, determine:

1. How much dispersion will increase in the new link.
2. Normal lifetime of the new link by considering 3 dB penalty for equipment aging, 2 dB lower system gain, and 0.12 dB cable splicing loss per year.

16. Two 24-core fiber optic cables are used in the same trench to connect six telecommunication nodes in (1 + 1) configuration as shown in Fig. 8.26. If core allocation in the stations types A and C were as shown, determine:

1. Core allocation for station type B.
2. Totally how many cores should be employed for this network.

3. The network topology.
4. Repeat core allocation for a system with $(2 + 1)$ configuration.

17. Using some types of ULL fiber with 0.17 dB/km loss factor will reduce the link absorption loss with the same amount of dispersion specified in Example 8.10, find:

1. Power margin of the link.
2. How much dispersion will increase if some cores be continued up to $L' = 100\,\text{km}$.
3. What kinds of countermeasures can be employed to compensate the excess dispersion.

18. Prepare a simple software to support computer-aided design of the links based on:

- Leaky cable
- Waveguide
- Fiber optics

Then upgrade your software for optimization of different parameters related to a specific link.

Chapter 9
Selected Topics in Radiowave Propagation

9.1 Scope

Ever-increasing demands for line-of-sight (LOS) radiocommunications in UHF, SHF, and EHF frequency bands and future potential needs resulted in employing higher frequency bands. To meet future requirements, terahertz band has been an objective issue for ITU and radio research centers. New systems are introduced in the following categories:

- Optical radio links
- Infrared radio links

Wavelength of visible light extends from 4000 to 8000 Å corresponding to 375–750 THz, meaning that the selected band covers visible light and infrared spectrum.

The aforementioned radio systems operate based on the LOS propagation, and therefore this chapter may be viewed as a supplement to the line-of-sight radiowave propagation discussed in Chap. 7. It should be noted that some of the properties and principles stated for LOS radiocommunications are also valid here taking into account the higher frequency effects. For example, rain, snow, and aerosol attenuations are neglected for the frequencies less than the values indicated below:

- Rain: 10 GHz
- Dry snow: 50 GHz
- Aerosol: 100 GHz

However, for frequencies more than the specified values, those losses shall be considered for radio link design. Radio sector of ITU has performed some studies for the above issues concluding the following documents:

- Recommendation ITU-R, Rec. P.1814, issued 2007 related to prediction methods required for the design of terrestrial free-space optical links.

A. Ghasemi et al., *Propagation Engineering in Wireless Communications*,
DOI 10.1007/978-3-319-32783-9_9

- Recommendation ITU-R, Rec. P.1817, issued 2007 related to propagation data required for the design of terrestrial free-space optical links.
- Recommendation ITU-R, Rec. P.1621, issued 2003 and revised 2005 related to the propagation data required for the design of Earth-space systems operating between 20 and 375 THz.
- Recommendation ITU-R, Rec. P.1622, issued 2003, related to the prediction methods required for the design of Earth-space systems operating between 20 and 375 THz.

Because of the frequency selectivity of the propagation phenomena, some less important issues for UHF/SHF/EHF bands shall be taken into account for FSO link design. In addition, a number of new concepts such as molecular scattering, aerosol attenuation, and geometric effects shall be developed.

9.2 Optical Radio Links

9.2.1 Introduction

Radiowave, similar to visible light, is an EM wave which follows the Maxwell's equations and propagates in the Earth atmosphere with a velocity around 300,000 km/s. The use of higher frequency bands encounters a number of limiting factors among which the following are more significant:

- RF passive and active components
- Transmission line elements such as feeders, antennas, and connectors
- Propagation phenomena and high-frequency specific effects
- Attenuation of transmission medium

In optical fibers, radiowaves are transmitted in guided media using windows of 850, 1310, and 1550 nm wavelengths. Usually due to the properties of fiber material, the attenuation is low and lightwaves convey a large capacity traffic using optical multiplexing techniques such as WDM and DWDM. Based on low attenuation of single-mode fiber optics which is on the order of 0.25 dB/km, signals may be transmitted a long distance without any repeater.

However, some telecommunications requirements such as high-speed data, voice, and video signals may be handled through short- or long-haul networks, while a number of services such as broadcasting, mobile, satellite, and navigational aids shall be supported by radio systems.

These facts motivated some national and international bodies such as ITU and radio research centers to conduct a number of studies to investigate the application of the following systems:

- Radio systems operating between 20 and 375 THz
- Terrestrial free-space optical links

9.2.2 Main Atmospheric Effects

Radiocommunications in the optical or infrared frequency bands are subject to the Earth atmosphere phenomena considering their material, dimensions, chemical properties, and physical/geometrical aspects. The effects are due to a number of various phenomena including, but not limited to, the following issues:

- Atmospheric absorption
- Atmospheric scattering
- Scintillation
- Precipitation
- Aerosols
- Ambient sunlight
- Geometrical attenuation

In the following sections, each of the above phenomena is explained briefly.

9.2.3 Atmospheric Absorption

Atmospheric absorption is a frequency-selective phenomenon which occurs due to the interaction between optical radiation and existing molecules or atoms. In the atmosphere molecular absorption results from N_2, O_2, H_2, H_2O, CO_2, O_3, A_r, etc. The absorption coefficient depends on the type and density of gas molecules. The spectral variations of the absorption coefficient determine the absorption spectrum which its nature is based on the variations of quantized energy levels of the gas generated essentially by the electronic transitions, vibrations of the atoms, and rotation of the molecules.

An increase in the pressure or temperature tends to widen the spectral absorption lines by excitation of higher energy levels and by the Doppler effect. The transmission windows in the optical range for visible light and infrared (IR) as shown in Fig. 9.1 are:

- Visible and very-near IR: $\lambda = 0.4$–$1.4\,\mu\text{m}$
- Near IR or IR-I: $\lambda = 1.4$–$2.7\,\mu\text{m}$
- Mean IR or IR-II: $\lambda = 2.7$–4.3 and $\lambda = 4.5$–$5.2\,\mu\text{m}$
- Far IR or IR-III: $\lambda = 8$–$14\,\mu\text{m}$
- Extreme IR or IR-IV: $\lambda = 16$–$28\,\mu\text{m}$

Each kind of gaseous molecules has its own specific quantified energy levels and loses one or more photons under influence of an incident EM radiation and transition from an initial level e_i to a higher energy level e_f. The process only occurs if the incident wave frequency corresponds to one of resonance frequencies of the relevant molecule, given by:

$$v_0 = (e_f - e_i)/h \tag{9.1}$$

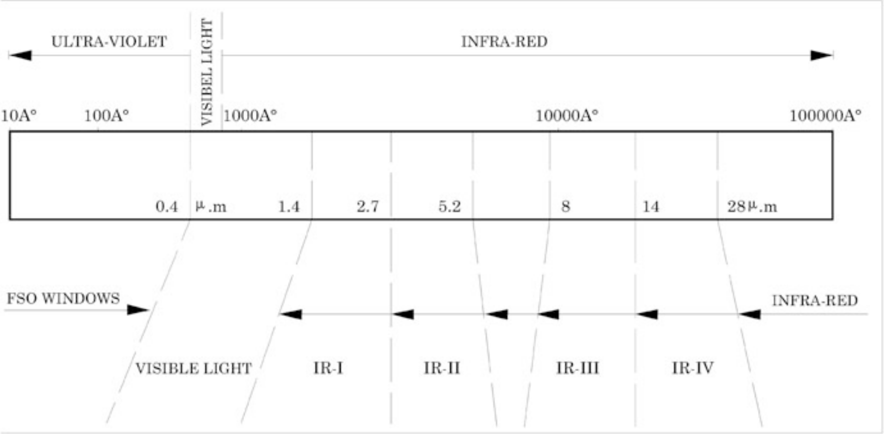


Fig. 9.1 Transmission windows in FSO

where:

v_0: Incident wave frequency in Hz

h: Plank's constant equal to 6.6262×10^{-34} J S

The fundamental parameters determining the absorption caused by molecular resonance are:

- Possible energy levels
- Probability of transition from e_i to e_f
- Intensity of resonance lines
- Natural profile of each line

Generally, the profile of each absorption line is modified by the Doppler effect when molecules are moving relative to the incident wave and by the collision effect due to the interaction of molecules. These phenomena lead to a spectral widening of the natural line of each molecule.

9.2.4 Atmospheric Scattering

Scattering is significant when the particle size is on the order of the incident EM wavelength. In FSO links, where RF frequency is between 100 and 1000 THz, the corresponding wavelength is from 3 to 0.3 µm; thus, atmospheric particles being in this range will scatter the EM wave. Atmospheric scattering in the FSO links consists mainly of the following types:

- Molecular scattering
- Aerosol scattering

Precipitation scattering is not considerable because of the size of rain drop, snowflake, or other types of precipitation compared with the EM radiated wavelengths.

9.2.4.1 Molecular Scattering

Molecular scattering results from the interaction of light with atmospheric particles whose sizes are smaller than the wavelength of the incident light. Scattering by atmospheric gas molecules as Rayleigh scattering contributes to the total attenuation of the EM radiation.

The extinction coefficient of molecular scattering denoted by $\beta_m(\lambda)$ can be approximated by the following expression:

$$\beta_m(\lambda) = A\,\lambda^{-4} \tag{9.2}$$

where:

$$A = 1.09 \times 10^{-3} \times \frac{P}{P_0} \times \frac{T_0}{T}\ \mathrm{km^{-1}m^4} \tag{9.3}$$

Parameters of the above expressions are:

- $\beta_m(\lambda)$: Molecular scattering coefficient (km^{-1})
- λ: Wavelength (μm)
- P: Atmospheric pressure (mbar)
- P_0: 1013 (mbar)
- T: Atmospheric temperature (K)
- T_0: 273 K

In general, β_m is a function of wavelength (λ), molecular density, air depolarization factor, and refractive index. Molecular scattering is negligible at infrared (IR) wavelength, while Rayleigh scattering generates blue wavelength much more strongly than other end of the visible (i.e., red) spectrum.

9.2.4.2 Aerosol Scattering

As defined in the ITU-R, P.310, aerosol is extremely fine solid or liquid particle suspended in the atmosphere. Its diameter generally lies between 0.01 and 100 μm. Fog, dust, and maritime spindrift particles are examples of aerosols.

Aerosol dimension is comparable to the wavelength of optical radiowaves resulting in aerosol scattering. Attenuation is a function of frequency and visibility. This phenomenon is the most restrictive factor to the deployment of free-space optical system at long distances. In the optical frequency range, it is mainly caused by mist and fog which can reach to 300 dB/km. The extinction coefficient due to the aerosol scattering denoted by β_n, is a function of wavelength, particle size distribution, real part of aerosol refractive index, radius of particle, and scattering cross section for a given type of aerosol.

Mie theory predicts the scattering cross section, assuming the particles are spherical and sufficiently separated so that the scattered field can be calculated assuming far field scattering. The scattering cross section strongly depends on the size of the aerosol compared to the wavelength and is a frequency-selective function for particles whose radii are less than or equal to the wavelength. It reaches its maximum value for a particle radius equal to the wavelength.

Since the aerosol concentration, composition, and size distribution vary temporally and spatially, it is difficult to predict attenuation by these aerosols. Although the concentration is closely related to the optical visibility, there is not a unique particle size distribution for a given visibility.

9.2.5 Scintillation

Scintillation is related to rapid and random fluctuation in one or more of characteristics such as amplitude, phase, polarization, and direction of arrival of a received signal, caused by refractive index fluctuations of the transmission medium. This phenomenon takes place under the influence of thermal turbulence by producing distributed cells of varying refractive index.

The produced cells cause scattering, multipath, and variation in the angle of arrival, resulting in the received signal level fluctuation called scintillation at frequencies between 0.01 and 200 Hz. Wave-front variations similarly cause time varying focusing and defocusing of the radio beam.

The amplitude and frequency of scintillation depend on the size of the cells compared to the diameter of the beam. Figures 9.2, 9.3, and 9.4 show this effect as well as the variations (amplitude, frequency) of the received signal.

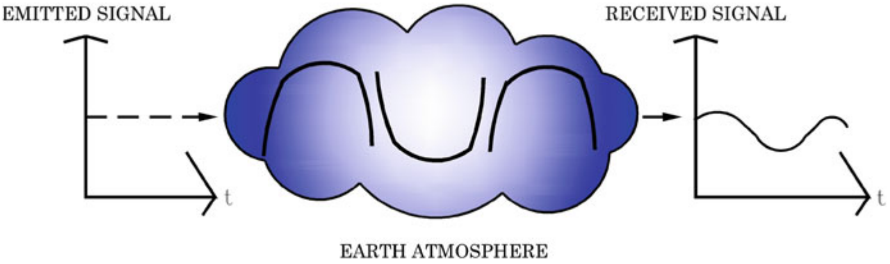


Fig. 9.2 Beam deviation due to large cells ($>\lambda$)

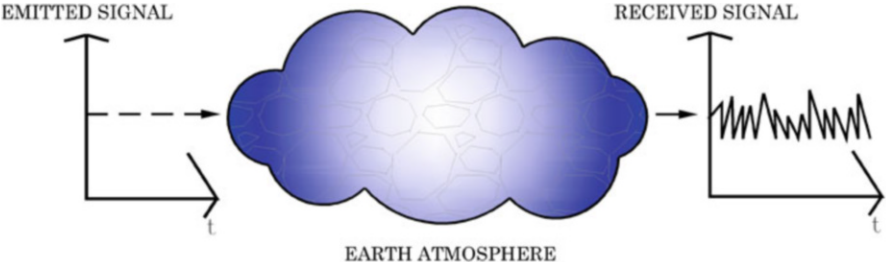


Fig. 9.3 Beam deviation due to small cells ($<\lambda$)

Fig. 9.4 Beam deviation due to mixed cells

9.2.6 Atmospheric Precipitation

Precipitation including rain and snow effects on the optical radiowaves is outlined in this section. However, the same approach, as specified for SHF/EHF line-of-sight links, is followed for FSO links, but due to frequency selectivity property of precipitation, its effects are different in magnitude.

9.2.6.1 Rain Attenuation

Rain attenuation is usually explained by specific rain attenuation coefficient denoted by γ_r and expressed in dB/km. An approximate expression for γ_r is given by:

$$\gamma_r = K\, R^{\alpha} \tag{9.4}$$

where K and α are real values and frequency dependent and R is the rainfall rate in mm/h exceeded for a given percentage of time. Recommendation ITU-R, P.837, gives rainfall rate for different locations of the world.

In Fig. 9.5, rain specific attenuation for infrared or optical radiowaves is given for different values of R. As indicated for $R_1 = 20$ mm/h and $R_2 = 100$ mm/h, the magnitude of γ_r is around $\gamma_{r1} = 8$ dB/km and γ_{r2}=24 dB/km, while similar values for 10 GHz are less than 1 dB/km.

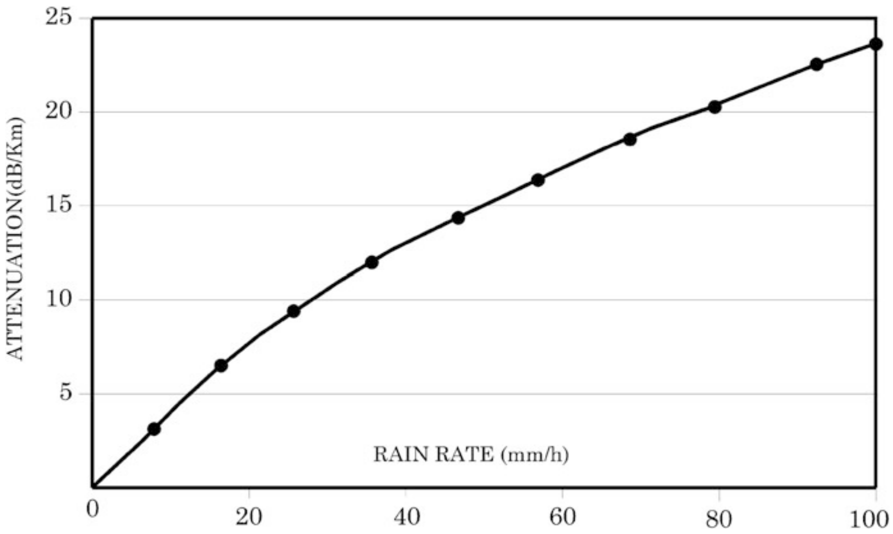


Fig. 9.5 Rain specific attenuation for infrared and FSO waves

Table 9.1 Snow parameters for γ_s

Type	α	b
Wet snow	$0.000102\ \gamma + 3.79$	0.72
Dry snow	$0.0000542\ \gamma + 5.50$	1.38

9.2.6.2 Snow Attenuation

Snow attenuation is usually explained by snow specific attenuation coefficient denoted by γ_s and expressed in dB/km. An approximate expression to estimate γ_s is given by:

$$\gamma_s = a \cdot S^b \tag{9.5}$$

where a and b are real values and wavelength-dependent parameters as indicated in Table 9.1 and S is snowfall rate in mm/h at each location:

For values of λ greater than 10 nm ($f \leq 30$ GHz), the snow specific attenuation coefficient is negligible, but at $\lambda = 1550$ nm ($f \approx 193.5$ THz), this figure for 4 mm/h snowfall is estimated to be 11 and 38 dB/km for wet and dry snow, respectively. In Fig. 9.6, the estimated attenuation at $\lambda = 1550$ nm ($f \approx 200$ THz) is shown versus snowfall rate up to 4 mm/h for wet and dry snow.

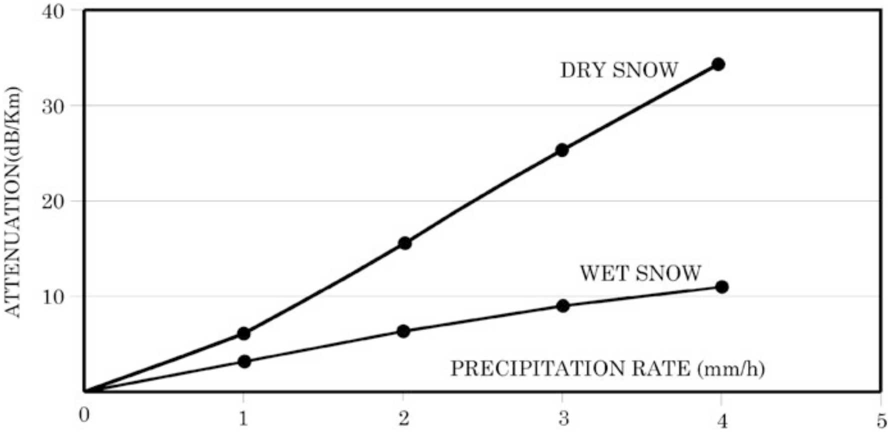


Fig. 9.6 Snow attenuation at $\lambda = 1550\,\text{nm}$

9.2.6.3 Hail Attenuation

Hail is another atmospheric precipitation with individual hailstone diameter sometime reaching 20 mm or more. Intensity of hailfall is normally high but for very short period (in the order of minutes) and with very low occurrence probability. In spite of high attenuation of hailfall resulting in total outage, its time percentage is very low and may be ignored in the link design calculations for the terrestrial networks.

Assuming two times of hailfall per year each lasting 5 min, then total outage at the worst case is $(2 \times 5)/(365 \times 24 \times 60) \approx 0.00002$ corresponding to 0.002 % which in comparison with 0.1 % unavailability (99.9 % availability) for high-grade networks can be neglected.

9.2.6.4 Experimental Results

Cumulative distribution of attenuation measured at 850 nm wavelength on a 850 m path due to fog, rain, snow, rain plus snow, and all hydrometeors is presented in the ITU-R, Rec. P.1817. The test was conducted during a 1-year period in Prague by experts from Czech Republic, and results are given in Fig. 9.7.

All fading events were classified according to the meteorological conditions causing a particular fade event. The meteorological conditions were identified employing a camera image of the area between the transmitter and receiver and using data obtained from an automatic meteorological station located near the receiver. Fading events caused by fog and by snow were the most serious.

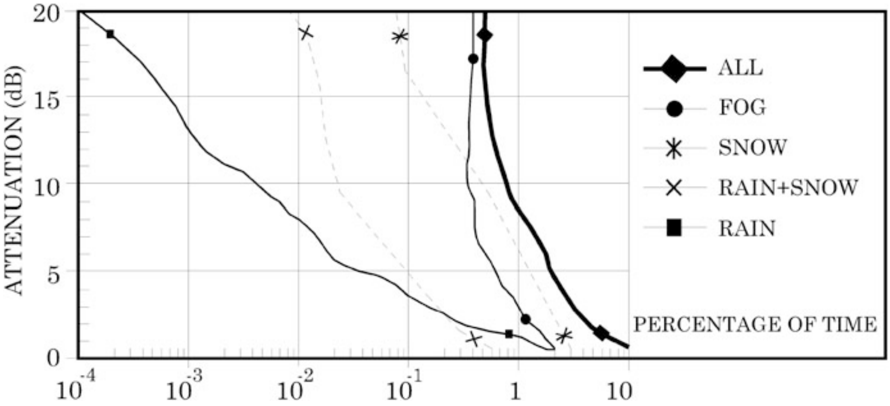


Fig. 9.7 Cumulative attenuation distribution for different path conditions

9.2.7 Aerosol Absorption

Aerosols are very small suspended particles in the atmosphere with diameter in the range of 0.01–100 μm which absorb energy of EM waves resulting in the atmospheric attenuation. Aerosols' attenuation depends on their chemical properties, size, and concentration.

In maritime environments they are primarily due to droplets of water in different forms (foam, fog, drizzle, and rain), salt crystals, and various particles of continental origin. Type and density of continental particles depend on the height and characteristics of the neighboring coast.

Aerosol absorption coefficient denoted by α_n is a function of the following factors:

- Optical beam wavelength
- Aerosol size distribution per unit volume
- Aerosol radius
- Aerosol refractive index (imaginary part)
- Absorption cross section for a given type of aerosol

The refractive index of aerosol depends on its chemical composition and incident beam's wavelength. Real part of it causes scattering and imaginary part results in absorption. In the visible and near-infrared spectral regions, the imaginary component of refractive index is extremely low and can be neglected in calculation of total attenuation, while in the far-infrared case, it shall be taken into account.

The absorption cross section value depends on the aerosol size, refractive index, and incident beam's wavelength. It represents the portion of an incident wave where the absorbed power is equal to the incident power.

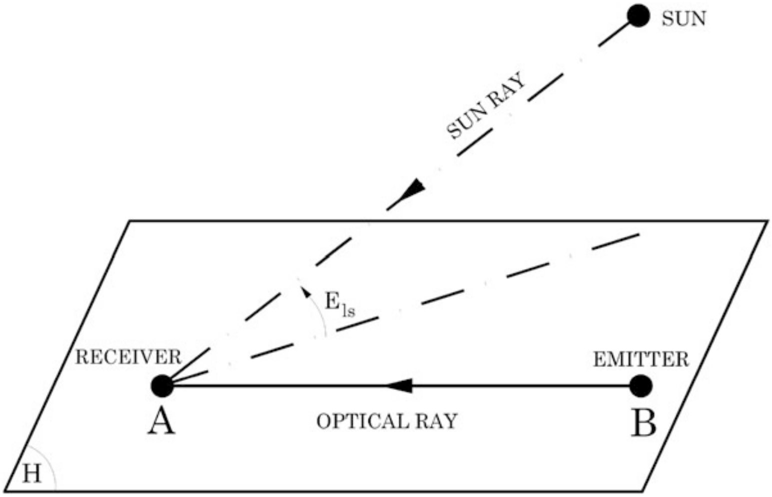


Fig. 9.8 Geometry of solar and FSO beams

9.2.8 Ambient Sunlight Effect

When solar ray directly or via reflection is in or near instantaneous field of view (IFOV) of an optical receiver, it makes adverse effects on receiving the required signals, called interference. The problem becomes severe when the Sun ray is parallel to the optical link and the Sun power penetrating inside the receiver is greater than the power received from the emitter. Solar interference is usually reduced by arranging for the receiver to be positioned so that the Sun is always off-axis.

As depicted on Fig. 9.8, the power radiated by the Sun is defined in W/m^2 by the following expression:

$$P_r = 1200 - \cos\left(\frac{\pi}{2} - E_{ls}\right) \tag{9.6}$$

where E_{ls} and P_r are solar elevation angle in radian and radiated power in W/m^2, respectively. The received power is given by:

$$P_s = F_s \cdot P_r \cdot S_c \cdot W_r / 100 \tag{9.7}$$

$$F_s = 8.97 \times 10^{-13}\lambda^5 - 4.65 \times 10^{-9}\lambda^4 + 9.37 \times 10^{-6}\lambda^3 - 9.067 \times 10^{-3}\lambda^2 + 4.05\lambda - 5.7 \tag{9.8}$$

In (9.7) each parameter and its unit is:

P_s: Solar power received in W/m^2
F_s: Solar spectral power as a function of wavelength
P_r: Solar radiated power in W/m^2 as per expression (9.6)
S_c: Receiver capture surface area in m^2
W_r: Receiver bandwidth in nm
λ: Incident beam wavelength in nm

9.2.9 *Visibility*

The visibility is defined as the distance to an object where the image contrast drops to 2 % of its original value. This parameter is denoted by V and measured in m or km. The reference wavelength for measurement is 550 nm where the maximum intensity of the solar spectrum exists and is given by the Koschmieder relation:

$$V\,[\mathrm{km}] = \frac{3.912}{\gamma_{550[\mathrm{nm}]}} \tag{9.9}$$

where $\gamma_{550[\mathrm{nm}]}$ is the extinction coefficient of the medium due to the atmosphere and aerosol attenuation and scattering. In Table 9.2, reference data is given based on the international codes.

Table 9.2 International visibility code

International visibility code

Weather conditions	Precipitation			Visibility	Attenuation
			(mm/h)	(m)	(dB/km)
Dense fog				0	
				50	315
Thick fog				200	75
Moderate fog	Snow			500	28.9
Light fog		Storm	100	770	18.3
Very light fog				1000	13.8
		Strong rain	25	1900	6.9
Light mist				2000	6.6
		Average rain	12.5	2800	4.6
Very light mist				4000	3.1
		Light rain	2.5	5900	2
				10,000	1.1
Clear air		Drizzel	0.25	18,100	0.6
				20,000	0.54
Very clear air				23,000	0.47
				50,000	0.19

9.3 Optical Radio Link Design

To design a free-space optical (FSO) link, in addition to the selection of suitable wavelength, data rate, eye safety limits, and ambient solar radiation, losses due to the following major items shall be considered:

- Atmospheric absorption
- Scattering and scintillation adverse effects
- Microclimate environment and localized effects
- Atmospheric precipitation
- Link distance
- Link misalignment

In FSO links, because of narrow beamwidth, the clearance needed between the center of the beam and any obstruction is essentially equal to or more than the beam radius, while for radio links operating in UHF/SHF/EHF frequency bands, Fresnel zone clearance is enough. Also narrow beamwidth makes alignment of the laser communications terminal more critical.

9.3.1 Design Calculations

The primary disadvantage of FSO systems is their vulnerability to atmospheric adverse effects such as attenuation, scattering, and scintillation which can reduce link availability. Design calculations for the FSO links in line-of-sight (LOS) communications are outlined in this section by giving overall expression, required tables, and formulas.

9.3.1.1 Link Power Budget

A key parameter in the design of FSO links is the consideration of the power budget. Link margin denoted by M_L is defined as the excess power available above the relevant receiver sensitivity (threshold level). Link margin represents the amount of attenuation which may be tolerated by a given system at a given range and can be calculated in decibel (dB) by the following equation:

$$M_L = P_e - S_r - A_g - A_a - A_s - A_m \tag{9.10}$$

In the above equation, each parameter and its unit is:

P_e: Total power of the emitter, in dB_m

S_r: Sensitivity (threshold level) of the receiver in dB_m depending on the bandwidth/data rate

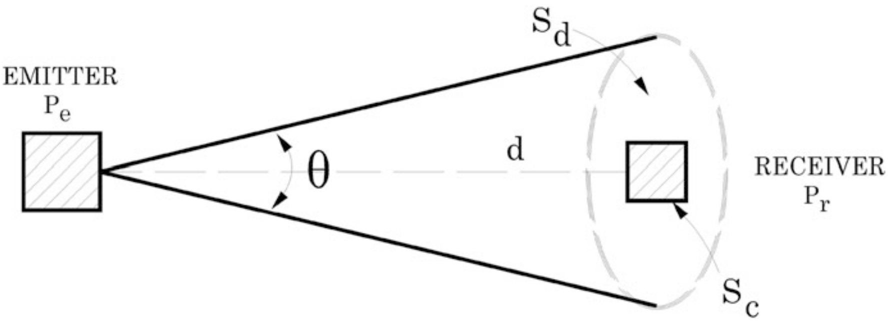


Fig. 9.9 Geometric attenuation concept in FSO link

A_g: Geometrical attenuation in dB due to transmitted beam spreading with distance
A_a: Atmospheric attenuation in dB due to absorption and scattering
A_s: Scintillation attenuation in dB due to atmospheric turbulence
A_m: Miscellaneous attenuation in dB including system-dependent losses such as misalignment of the beam direction, receiver's optical losses, beam wander, reduction in the receiver sensitivity because of ambient sunlight, etc.

9.3.1.2 Geometrical Attenuation

Geometrical attenuation is power loss between emitter and receiver in free-space condition. Even in the ideal and fully clear weather and neglecting all atmospheric attenuations due to absorption, scattering, scintillation, etc., optical beam diverges resulting in less power detected by the relevant receiver.

As shown in Fig. 9.9, the attenuation due to transmitted beam spreading with increasing range is called geometrical attenuation, A_g, and is given by the following formulas:

$$A_g\,[\mathrm{dB}] = 10\log\left(S_d/S_c\right) \tag{9.11}$$

$$S_d = \frac{\pi}{4}(d \cdot \theta)^2 \tag{9.12}$$

In the above expressions, each parameter and its unit is as follow:

S_c: Capture surface of the receiving system in m^2
S_d: Surface area of transmitting beam at distance d from the emitter in m^2
θ: Optical beam divergence in mrad
d: Distance between emitter and receiver in km

It is noted that Eq. (9.11) is valid for $S_d \geq S_c$. In the case of short links where the capture area to be greater than the beam area and all emitting energy is collected ($S_d < S_c$), the value of A_g should be set to zero.

9.3.1.3 Atmospheric Attenuation

Atmospheric attenuation can be presented by γ_a as a coefficient for the atmosphere specific attenuation. It may be written as the sum of two terms:

$$\gamma_a = \gamma_c + \gamma_e \tag{9.13}$$

where:

γ_c: Specific attenuation under clear air, i.e., due to the presence of normal atmosphere gaseous molecules only

γ_e: Specific attenuation due to the occasional presence of atmospheric phenomena such as fog, mist, haze, drizzle, rain, snow, hail, etc.

The atmosphere is a time and location varying transmission medium which cause a varying γ_a based on a stochastic process. However, imposing limits on system availability and its effects are generally treated statistically, and, for link design purposes, its predetermined worst value shall be considered.

9.3.1.4 Clear-Air Attenuation

Clear air consisting of the lower portion of the atmosphere is a gaseous mixture of $N_2, O_2, H_2, H_2O, CO_2, O_3$, and inert molecules with different and slightly varying densities. Due to small diameter of the molecules, their scattering attenuation in optical spectrum is negligible.

In spite of scattering small attenuation, the air absorption is important and shall be taken into account in the optical communications link. Clear-air (sky) absorption depends on the frequency and concentration of optical (laser) beam and has selective effects on some of molecules including H_2O, CO_2, O_3, and O_2 in the infrared spectrum.

Based on the above descriptions, some specific frequency bands called "transmission windows" are employed in the optical communications where the values of wavelengths or transmission windows are around 690, 780, 850, and 1550 nm which include infrared and some portion of visible light spectrum.

In urban and suburban areas where industrial plants and high traffic generate a great amount of chemical gaseous and aerosols, optical communications may benefit from a different wavelength to reduce the air attenuation.

Table 9.3 Atmospheric aerosols scattering regimes

Scattering regime description	Rayleigh	Mie	Geometrical
Criteria	$r \lesssim \lambda$	$r \approx \lambda$	$r \gtrsim \lambda$
Scattering attenuation coefficient, $Q(\lambda)$	λ^{-4}	$\lambda^{-1.6} \sim \lambda^{\circ}$	λ°
Typical scatter	Air, molecules, haze	Haze, fog, aerosol	Rain, snow, hail

9.3.1.5 Air Excess Attenuation

Air excess attenuation refers to scattering of the incident beam due to particles with occasional presence in the atmosphere. Among these aerosols and particles, fog, cloud, dust storms, drizzle, rain, snow, hail, chemical smokes, and vapor may be addressed. Adverse effects of the mentioned particles will cause excess losses due to scattering. This phenomenon results in the reduced flux density of the incident beam with a different nature (in the original direction) when compared with the absorption loss.

Size of scatter particles in comparison with wavelength of the optical beam determines the scattering regime such as Rayleigh, Mie, and geometric to be selected for evaluation.

As specified in Table 9.3, because of the Rayleigh regime relation, $Q(\lambda) \sim \lambda^{-4}$, the air molecular scattering contribution to the total attenuation is negligible. For particles that are much larger than the wavelength, scattering can be described by geometrical optics which is independent of the optical wavelength, but for particles with sizes comparable to λ, Mie scattering theory shall be applied.

9.3.1.6 Fog Specific Attenuation Coefficient

Since an analytical approach often is not practical to compute γ_f, empirical methods have been adopted for the FSO calculations by using visibility. As explained in Sect. 9.2.9, visibility or visual range is the distance that light decreases to 2 % of the original power. An empirical simplified formula for fog specific attenuation coefficient, γ_f in dB/km is:

$$\gamma_f = \frac{3.91}{V}(\lambda/550)^{-q} \tag{9.14}$$

where the components and their units are:

V: Visibility in km
λ: Wavelength in nm

q: A coefficient dependent on the size distribution of the scattering particles experimentally determined by:

$$\begin{aligned} q &= 1.6 \quad \text{for } V > 50\,\text{km} \\ &= 1.3 \quad \text{for } 6\,\text{km} < V < 50\,\text{km} \\ &= 0.58\sqrt[3]{V} \quad \text{for } V < 6\,\text{km} \end{aligned}$$

To obtain the value of γ_f for a given percentage of time, the visibility value for this percentage shall be applied in formula (9.14).

9.3.1.7 Rain and Snow Specific Attenuation Coefficient

Excess losses due to rain and snow can be expressed in terms of the related specific attenuation coefficients denoted by γ_r and γ_s, respectively. These coefficients are calculated by formulas and tables given in Sects. 9.2.6.1 and 9.2.6.2.

9.3.1.8 Scintillation Fading

Scintillation as a major atmospheric process affects the performance of the FSO link by severe fluctuations in the received signal level. Atmospheric turbulence produces temporary pockets of air with slightly different temperatures, densities, and indices of refraction. Data may be lost due to beam wander and scintillation as the FSO beam becomes deformed propagating through inhomogeneous medium. The depth of each effect depends on the size of turbulence cells with respect to the beam diameter.

If the sizes of the turbulence cells are larger than the beam diameter, the optical beam bends as a whole, causing signal loss if the beam wanders off the receiver aperture. Longer wavelength has less beam wander than shorter one, although the wavelength dependence is weak.

More commonly, if the sizes of the turbulence cells are smaller than optical beam diameter, ray bending and diffraction cause distortions in the optical beam wave front. This results in temporal fluctuations in the optical beam intensity, known as scintillation, at the receiver with a frequency spectrum from 0.01 to 200 Hz.

Tropospheric scintillation effects are generally studied from the logarithm of the amplitude χ in decibels of the received signal. This parameter is defined as the ratio (in decibels) of the instantaneous amplitude to its average value. The intensity and the fluctuation rate called scintillation frequency increase with λ. For a plane wave and weak turbulence, the scintillation variance σ_X^2 can be expressed by the following relation:

$$\sigma_X^2 = 23.17\, k^{7/6} \cdot C_n^2 \cdot L^{11/6} \tag{9.15}$$

where the components and their units are:

$k = \frac{2\pi}{\lambda}$: Wave number in m^{-1}
L: Length of FSO path in m
C_n^2: Refractive index structure parameter in $\mathrm{m}^{-2/3}$

The scintillations have peak amplitude of $4\sigma_X$, and the attenuation due to scintillation is $2\sigma_X$. For strong turbulence, saturation of the variance given by the above relation is obtained.

The structure parameter, C_n^2, has a different value at optical wavelengths than at millimeter wavelengths. Scintillation at millimeter wavelengths is primarily due to humidity fluctuations, while at optical wavelengths, this phenomenon is primarily a function of the temperature. At millimeter λ, C_n^2 is approximately equal to $10^{-13}\,\mathrm{m}^{-2/3}$ (in general between 10^{-14} and $10^{-12}\,\mathrm{m}^{-2/3}$), and at optical λ, C_n^2 is approximately equal to about $2 \times 10^{-15}\,\mathrm{m}^{-2/3}$ (in general between 10^{-16} and $10^{-13}\,\mathrm{m}^{-2/3}$).

Figure 9.10 illustrates the variation of the attenuation of a 1550 nm wavelength optical beam for weak, mean, and strong turbulence at distances up to 2000 m. As shown, attenuation increases with turbulence. Table 9.4 indicates the turbulence effect on optical and radiowave propagation.

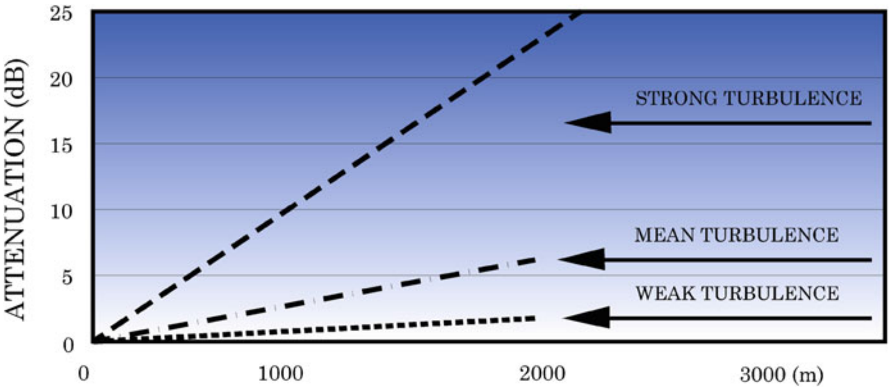


Fig. 9.10 Scintillation variation versus distance

Table 9.4 Scintillation fade depth expected for 1 km

	Optical waves			Millimeter waves		
Turbulence	$(C_n)^2$	$\lambda = 980$ nm	$\lambda = 1550$ nm	$(C_n)^2$	$f = 40$ GHz	$f = 60$ GHz
Low	10^{-16}	0.5	0.39	10^{-15}	0.03	0.03
Moderate	10^{-14}	5	3.87	10^{-13}	0.09	0.11
High	10^{-13}	17	12.25	10^{-12}	0.27	0.35

9.3.2 FSO Link Design

9.3.2.1 System Gain

The effects of all system-dependent parameters which are related to neither propagation phenomena nor transmission medium properties are called system gain and can be calculated by the following expression:

$$S_G = P_e - S_r - A_m \tag{9.16}$$

where:

S_G: System gain in dB$_m$
P_e: Emitter power in dB$_m$
S_r: Receiver sensitivity in dB$_m$
A_m: Miscellaneous attenuation representing all other system-dependent losses such as receiver optical loss, beam wander loss, misalignment and ambient sunlight attenuation, etc.

9.3.2.2 Link Equation

Overall equation of an FSO link with length d [km] between an emitter and a receiver has a general form as below:

$$M_t = S_G - A_g - A_s - (\gamma_c + \gamma_f + \gamma_r + \gamma_s)\, d \tag{9.17}$$

All terms are based on the prior definitions and can be calculated or estimated using the following steps:

Step 1: Select an appropriate wavelength among the specified atmospheric transmission windows mentioned in Sect. 9.2.3
Step 2: Calculate system gain (S_G) based on selected equipment performance characteristics and other specified system-dependent factors as explained in previous Sect. 9.3.2.1
Step 3: Calculate geometrical attenuation (A_g) by using related formula
Step 4: Calculate scintillation attenuation (A_s) by indicated procedure in ITU-R, Rec. P.1814, or Sect. 9.3.1.8)
Step 5: Calculate clear-air specific attenuation (extinction coefficient), γ_c, using procedure set in the ITU-R, Rec. P.1817. However, for wavelength within atmospheric transmission windows, this step can be neglected.
Step 6: Calculate fog specific attenuation (extinction coefficient), γ_f. In the absence of local data, typical values of visibility may be selected from Table 9.2.

Step 7: Calculate rain specific attenuation (extinction coefficient), γ_r, using Eq. (9.4) and relevant parameter table.

Step 8: Calculate snow specific attenuation (extinction coefficient), γ_S, using Eq. (9.5) and Table 9.2

Step 9: Calculate final fade margin, M_t, from Eq. (9.17).

9.3.2.3 Practical Issues

Major practical issues having key role in the FSO link design are summarized as follows:

1. Selection of proper wavelength from atmospheric transmission windows considering site-specific conditions in urban, suburban, and industrial areas due to the existence of chemical gases.
2. Observing international safety regulations which limit the maximum output power of optical systems for "eye safe" operations. At $\lambda = 1550\,\text{nm}$, the regulatory agencies allow approximately 100 times more power than for shorter wavelengths around 850 nm within visible light spectrum.
3. Adverse effects of site environmental conditions because of atmospheric precipitation and aerosols. Weather conditions and in particular the local climate in the vicinity of the chosen link path will affect the occurrence of snow, hail, rain, shower, drizzle, fog, haze, aerosol, dust storms, and air suspended content that will lead to excess absorption and scattering of the emitted beam.
4. Low visibility decreases the effectiveness and availability of FSO systems. Selecting short distance between FSO terminals is a countermeasure to the negative impacts because of greater link margin.
5. At stations where FSO transceivers are located behind windows, the beam angle with the widow is critical. The beam should be perpendicular to the window with 5° margin to reduce bounce-back of the beam to its receptor. Also some windows contain glass or glass coating which may reduce the signal by 60 % or more to infrared rejection.
6. Optical transceiver mounting condition is very critical because of its very narrow beamwidth. Accurate alignment of the emitter and receiver is important, and any misalignment causes significant loss. The telescope mounts must be stable and strongly fixed in a location with minimum thermal changes.
7. Taking into account hot air rising through thermal vents for link path between buildings which results in atmospheric turbulence and scintillation at the receiver and also all potential changes due to future actions and trees increasing in heights.
8. The topography and the type of surface beneath an FSO link can significantly impact the performance of the communications. FSO links along rivers if across areas of open sea will often experience more fog and reflections.
9. Providing line-of-sight condition to secure required path clearance criteria for the FSO links. In this regard all obstructions shall be avoided clearly.

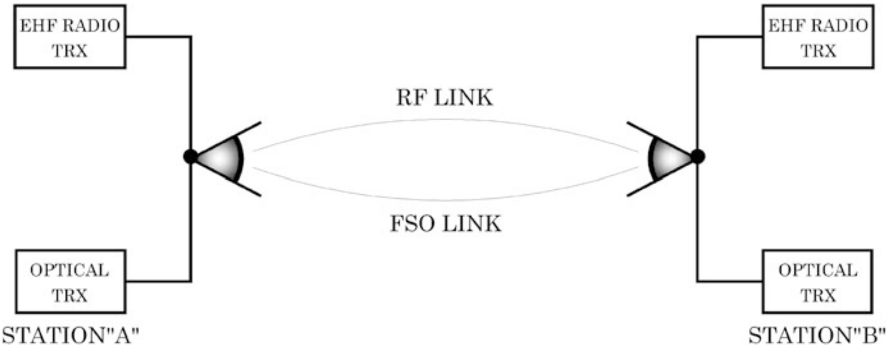


Fig. 9.11 RF/FSO cross band diversity configuration

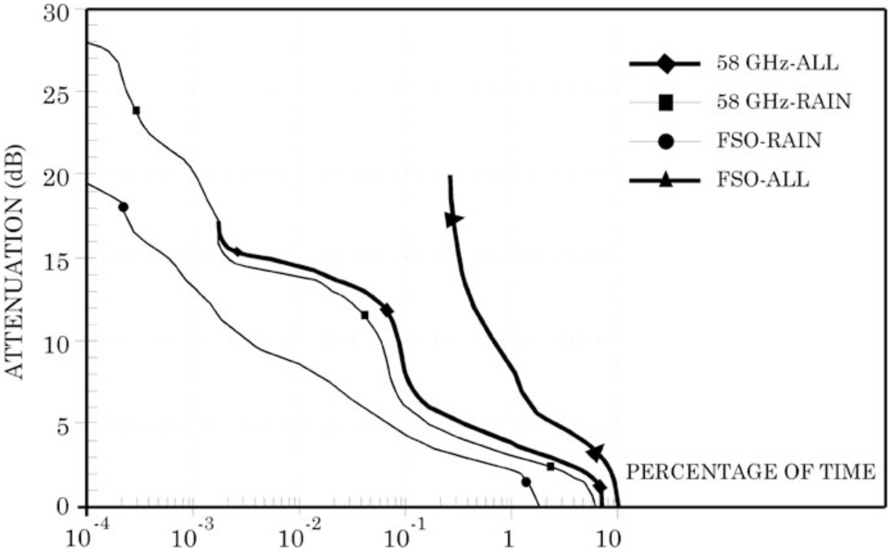


Fig. 9.12 RF and FSO attenuations for different time percentages exceeded

9.3.2.4 Diversity Reception

The use of cross band diversity (CBD) technique will improve system performance by providing higher availability and low outage time which may be imposed by deep fading. As shown in Fig. 9.11 between terminals "A" and "B," there are two links simultaneously, i.e., one RF link and one optical link through separate transceivers (TRX) at each side.

Figure 9.12 presented in the ITU-R, Rec, P.1817, compares attenuation measurements at 58 GHz and an optical link on the same path due to all hydrometeors and rain only.

The optical path has less attenuation than millimeter wave path during rain events. Hybrid radio/optical (RF/FSO) systems can improve FSO link performance by taking advantage of the fact that an RF path is attenuated by rain but is insensitive to fog. In contrast, an optical path is heavily attenuated by fog and is relatively insensitive to rain.

Annual cumulative distributions depicted in Fig. 9.11 gives an estimation of the performance of a hypothetical hybrid RF/FSO cross band system. Assuming the RF and FSO links with similar 20 dB fade margin (FM) used in a hybrid diversity configuration, the RF part mitigates during non-rain condition while the FSO part mitigates during rain event; thus, the overall performance will be improved.

9.4 Radiowave Propagation in 20–375 THz

The frequency band from 20 to 375 THz has been allocated by ITU to certain space-based communications in near Earth and deep space environments. Effects of main phenomena and propagation data and prediction methods are given in the radio recommendations P.1621 and P.1622. This section includes a brief description regarding major issues affecting radiowave propagation in this frequency band.

9.4.1 Main Effects of Atmosphere

Due to the application of this band for line-of-sight radiocommunications, the performance of the radio systems operating in 20–375 THz is subject to atmospheric line-of-sight conditions. The Earth atmosphere is complex and dynamic and will affect the performance of the received signals. Main atmospheric effects include:

- **Absorption**
  Molecules of atmospheric gases along the propagation path absorb radiowave energy resulting in an overall loss in signal amplitude.
- **Scattering**
  Existing particles, along the propagation path and ranging from frequency of one wavelength to many wavelengths, redirect the beam in terahertz band named scattering which results in an apparent loss in amplitude of the received signal.
- **Refraction**
  Changing of atmosphere density along the propagation path results in refraction of the radiowaves. This will affect geometrical line-of-sight condition due to apparent movement in the position of the transmitting source.
- **Turbulence**
  Thermal variations in the atmosphere result in fluctuation of amplitude and phase of the received signal.

Table 9.5 Standard astronomical filters

Filter	*Q*	*N*	*M*	*L′*	*L*	*K*	*H*
Center frequency	15	30	63	79	86	136	180
Wavelength	20.25	10.1	4.80	3.80	3.50	2.20	1.65
Filter	*J*	I_J	I_S	*R*	*V*	*B*	*U*
Center frequency	240	330	370	430	560	700	830
Wavelength	1.25	0.90	0.80	0.70	0.54	0.43	0.36

9.4.2 Absorption

Molecular absorption of the atmosphere using a line-by-line calculation method, similar to Annex 1 of ITU-R recommendation No. P.676, results in very high attenuation for 1–10 THz band. Above 10 THz, the absorptive characteristics of the atmosphere again become low and favorable for radiowave propagation in some specific windows.

The windows of low atmospheric absorption are identified within the astronomical standard filters in Table 9.5 (all frequencies are in THz and all wavelengths are in µm). As absorption is dependent on local atmosphere conditions such as temperature, pressure, and chemical composition, the bandwidth of filters does not necessarily correspond with the bandwidth of standard filters.

The U, B, V, R, and I_S windows are related to infrared to ultraviolet (IR∼UV) spectrum which is discussed in Sects. 9.2 and 9.3.

9.4.3 Scattering

Atmospheric scattering results in the received signal level reduction due to redirection of the transmitted EM energy away from the intended propagation path. The scattering characteristics of the atmosphere are dependent on the size of the particles present in the beam path. Scattering can be characterized in the following forms:

- Mie scattering when particles with diameters approximately equal to the beam wavelength appear along the propagation path.
- Rayleigh scattering when particles with diameters much smaller than the beam wavelength appear along the propagation path.

Specific attenuation of Rayleigh and Mie scatterings are given in Fig. 9.13 for standard atmosphere at sea level based on Rec. ITU-R, P.1621.

It should be noted that when particle size is much larger than wavelength along the propagation path, wavelength-independent scattering occurs which is most accurately described by diffraction theory.

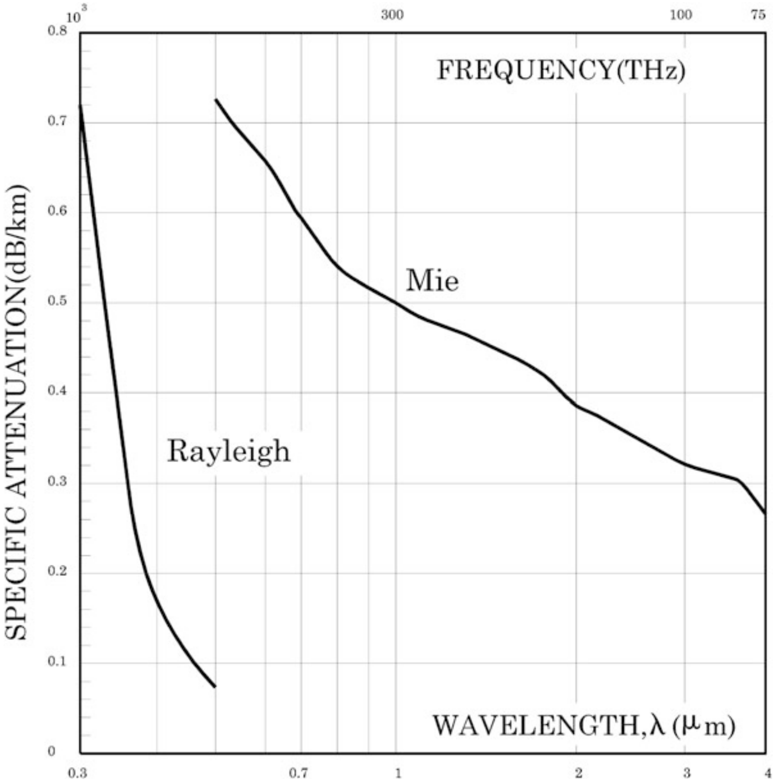


Fig. 9.13 Specific attenuation for standard atmosphere at sea level

9.4.3.1 Mie Scattering

The atmosphere exhibits Mie scattering when the particles of roughly the same physical diameter as the wavelength of the EM waves are present along the propagation path. Mie scattering is a complex function of the size, shape, and number of particles. Distribution of particle size and shape along the ray path is a function of the path profile for both water vapor content and wind speed. Aerosols and microscopic water particles are the predominant components of Mie scattering at frequencies between 20 and 375 THz (15 and 0.8 μm). In this frequency range as shown in Fig. 9.13, Mie scattering is significantly greater than Rayleigh scattering.

9.4.3.2 Rayleigh Scattering

The atmosphere exhibits Rayleigh scattering when the particles of the much shorter physical diameter than wavelength of the EM waves are present along the propagation path. At frequencies above 20 THz ($\lambda < 15\,\mu\text{m}$), Rayleigh scattering occurs due to interactions between the EM wave and polar molecules of atmosphere gases.

Received signal loss due to Rayleigh scattering as shown in Fig. 9.13 is negligible for frequencies below 375 THz, while its impact on transmitted signal becomes significant and comparable to Mie scattering at about 1000 THz. The major impact of Rayleigh scattering is introduction of background noise into receivers at both directions. The primary noise source for Earth stations operating with spacecraft is due to Rayleigh scatter of sunlight during daytime operations. Spacecraft pointed at the Earth will also encounter noise from sunlight reflected from Earth surface.

9.4.4 Turbulence

Turbulence adverse effects on radiowave propagation are as follows:

- **Amplitude Scintillation**
  The amplitude scintillation is caused by a spatially redistribution of EM energy across the surface of the wave front randomly in time. The strength of scintillation is measured in terms of the variance of the beam amplitude.
- **Angle of Arrival**
  Turbulence-induced fluctuations in the apparent angle of arrival of the received beam are due to variations of the refractive indices of the parcels of air along the propagation path. The effects of these fluctuations in the Earth-to-space direction are negligible. Typical r.m.s angle-of-arrival variations are in the order of 1 μrad resulting in small effects. However, in the space-to-Earth direction the r.m.s fluctuations are more in the order of several μrad and must be considered.
- **Beam Wander**
  Beam wander is the displacement of the beam from the intended propagation direction. Beam wander is significant in the Earth-to-space direction and can be in the order of a beamwidth which can potentially be mitigated through the use of multiple beams or a transmitter controlled with a tracking device. Beam wander has no significant effect in the space-to-Earth direction.
- **Beam Spreading**
  Beam spreading is the increase in the diameter of a beam, beyond that already occurring due to divergence, as a result of propagating through turbulence in the atmosphere. Beam spreading results in a reduced signal level arriving at the receiver due to the transmitted energy being spread over a larger area. However, the amount of spreading induced by the atmosphere is typically very small with respect to divergence and does not account for an appreciable loss of signal in both directions.

Appendix A
Logarithmic System of Units

A.1 Introduction

This appendix deals with the concepts and fundamentals of the logarithmic units and their applications in the engineering of radiowave propagation. Use of these units, expressing the formulas and illustrating figures/graphs in the logarithmic systems are common and frequently referred in the book.

A.2 Definition

According to the definition, logarithm of the ratio of two similar quantities in decimal base is called "bel" and ten times of it is called "decibel."

$$\text{bel} = \log_{10}\left(\frac{p}{p_r}\right)$$

$$\text{decibel} = [\text{dB}] = 10\ \log_{10}\left(\frac{p}{p_r}\right)$$

As the above formula suggests, it is a logarithmic scale and due to the persistent usage of decimal base in the logarithmic units, it is normally omitted from the related symbol for simplicity.

Since values in the logarithmic scale are the logarithm of the ratio of two similar quantities, hence, they are dimensionless and measured in the same unit. In other words, the unit of denominator, p_r, is the base of comparison and includes the required unit.

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To indicate the unit of the base in the logarithmic system of units, one or few characters are used according to the following examples:

dB_w: decibel unit compared to 1 W power
dB_m: decibel unit compared to 1 mW power
dB_{kw}: decibel unit compared to 1 kW power

Example A.1. Output power of a transmitter is 2 W; state its power in dB_m, dB_w, and dB_{kw}.

Solution.

$$P_t[dB_m] = 10 \ \log \frac{2 \times 10^3}{1 \,\mathrm{mw}} = 33 \ dB_m$$

$$P_t[dB_w] = 10 \ \log \frac{2}{1 \,\mathrm{w}} = 3 \, dB_w$$

$$P_t[dB_{kw}] = 10 \ \log \frac{2 \times 10^{-3}}{1 \,\mathrm{kw}} = -27 \, dB_{kw}$$

■

A.3 Basic Formulas

Applying the decibel units necessitates the frequent usage of logarithm; thus, it is essential to review the following basic mathematical formulas:

1. $\log_{10}^{a} = P \iff a = 10^P \iff \mathrm{Antilog}_{10} P = a$
2. $\log(a_1 \times a_2 \times \cdots \times a_n) = \log^{a_1} + \log^{a_2} + \cdots + \log^{a_n}$
3. $\log \ a^{(\frac{p}{q})} = (\frac{p}{q}) \log \ a$
4. $\log(\frac{a}{b}) = \log \ a - \log \ b$
5. $\log \ \sqrt[m]{a} = \frac{1}{m} \log \ a$

A.4 Common Logarithmic Quantities

Most of quantities used in the radio-communications are defined in terms of logarithmic units. Main logarithmic units used in this book are indicated in Table A.1.

In addition to the aforementioned cases, all of the quantities mentioned in the sequel are normally defined in dB:

- Polarization loss, PL
- Cross polarization discrimination loss, XPD
- Antenna front to back ratio, F/B
- C/N, S/N, E/N

Table A.1 Main logarithmic units

No.	Quantity	Base	Sign	No.	Quantity	Base	Sign
1	Gain/loss	Ratio	dB	8	Noise temperature	K (kelvin)	dB/K
2	Power	Watt	dB_w	9	Bandwidth	Hertz	dB_{Hz}
3	Power	Milliwatt	dB_m	10	Bit rate	b/s	$dB_{b/s}$
4	Power	Kilowatt	dB_{kw}	11	Power flux	w/m^2	dB_{w/m^2}
5	Antenna gain	Isotropic	dB_i	12	Noise power	watt	dB_{KTB}
6	Antenna gain	Dipole	dB_d	13	Field intensity (strength)	microvolt per meter	$dB_{\mu V/m}$
7	Voltage	Microvolt	$dB_{\mu V}$	14	Boltzmann coefficient	Kelvin/Joule	$dB_{J/K}$

- Gain or loss factors such as FSL, passive reflector gain, feeder loss, rain loss, etc.

A.5 Principles of Logarithmic System of Units

Rule 1: The logarithmic system of units is dedicated only for scalar quantities. If this unit is used for a vector quantity, it implies the magnitude of the vector quantity.

Rule 2: In the logarithmic system of units, mathematical operations are simplified compared to the ordinary system of units (IS).

Rule 3: The logarithmic scale when compared with the ordinary system of units presents large quantities related to the reference unit in a compact form while its role for small quantities is vice versa as follows:

$$\begin{array}{lll lll}
10 & \Longleftrightarrow & 10\text{ dB} & 0.1 & \Longleftrightarrow & -10\text{ dB} \\
100 & \Longleftrightarrow & 20\text{ dB} & 0.01 & \Longleftrightarrow & -20\text{ dB} \\
1000 & \Longleftrightarrow & 30\text{ dB} & 0.001 & \Longleftrightarrow & -30\text{ dB} \\
\vdots & & & \vdots & & \\
10^n & \Longleftrightarrow & 10n\text{ dB} & 10^{-n} & \Longleftrightarrow & -10n\text{ dB}
\end{array}$$

In radio-communications most of curves, graphs, and plots are normally illustrated on the logarithmic scaled axis for better presentation and simpler interpretation.

A.6 Advantages of Logarithmic System of Units

Applications of the logarithmic system of units have dominant advantages as specified below:

- Simplicity of the mathematical operations
- Much better presentation
- Better understanding and more simple interpretation

As an example, the following formula indicates the free-space loss in the ordinary (metric) system of units:

$$\mathrm{FSL} = \frac{(4\pi d)^2 \ \cdot f^2}{C^2}$$

The same formula in the logarithmic system of units is given as bellow:

$$\mathrm{FSL}\ [\mathrm{dB}] = 92.4 + 20\ \log f\ \cdot\ d$$

which is more popular in the technical calculations related to the radiowave propagation. It should be noted that every quantity presented in the logarithmic system of units can be easily transformed into the ordinary (metric) system of units or vice versa.

Example A.2. Equivalent isotropic radiated power of a transmitter is $43\,\mathrm{dB}_w$ (i.e., $\mathrm{EIRP} = 43\,\mathrm{dB}_w$); find:

1. Equivalent radiated power in terms of kW.
2. Assuming $37\,\mathrm{dB}_i$ antenna gain, determine antenna directivity in the metric system of units.
3. Transmitter power in watts.

Solution. 1.

$$P_e = \mathrm{Antilog}\left(\frac{43}{10}\right) = 20{,}000\,\mathrm{W} \ \Rightarrow\ P_e = 20\,\mathrm{kW}$$

2.

$$G_t[\mathrm{dB}] = 37\ \mathrm{dB}_i \ \Rightarrow\ G_t = \mathrm{Antilog}\left(\frac{37}{10}\right) = 5000$$

3.

$$\mathrm{EIRP}[\mathrm{dB}_w] = P_t[\mathrm{dB}_w] + G_t[\mathrm{dB}_i]$$

$$P_t[\mathrm{dB}_w] = 43 - 37 = 6\ \mathrm{dB}_w \ \Rightarrow\ P_t = \mathrm{Antilog}\left(\frac{6}{10}\right) = 4\,\mathrm{W}$$

■

Due to the nature of mathematical operations in the ordinary and logarithmic systems, it is important to know the method to be used for every expression or formula.

Different methods may be employed in technical books and papers. The method which is applied in this book uses brackets [ ] for the logarithmic units as seen in the following examples:

$$P_r[\mathrm{dB}_w] = P_t[\mathrm{dB}_w] + G_t[\mathrm{dB}_i] + G_r[\mathrm{dB}_i] - \mathrm{FSL}[\mathrm{dB}] - L_m[\mathrm{dB}]$$

or

$$\mathrm{EIRP}[\mathrm{dB}_m] = P_t[\mathrm{dB}_m] + G_t[\mathrm{dB}_i] - L_t[\mathrm{dB}]$$

or

$$L_{bf}[\mathrm{dB}] = P_t[\mathrm{dB}_w] - E[\mathrm{dB}_{\mu\mathrm{V/m}}] + 20\ \log f[\mathrm{GHz}] + 167.2$$

Appendix B
ITU-R Recommendations P-Series

Radiowave Propagation	
P.310	Definitions of terms relating to propagation in non-ionized media
P.311*	Acquisition, presentation, and analysis of data in studies of tropospheric propagation
P.313	Exchange of information for short-term forecasts and transmission of ionospheric disturbance warnings
P.341	The concept of transmission loss for radio links
P.368	Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz
P.369	Reference atmosphere for refraction Note-Suppressed on 24/10/97 (RA-97). This Recommendation has been replaced by Rec.ITU-R P.453-6
P.370	VHF and UHF propagation curves for the frequency range from 30–1000 MHz. Broadcasting services Note-Suppressed on 22/10/01 (CACE/233)
P.371	Choice of indices for long-term ionospheric predictions
P.372*	Radio noise
P.373	Definitions of maximum and minimum transmission frequencies
P.434	ITU-R reference ionospheric characteristics and methods of basic MUF, operational MUF, and ray path prediction Note-Suppressed on 24/10/97 (RA-97). This Recommendation has been replaced by Rec.ITU-R P.1239 and ITU-R P.1240
P.435	Sky wave field strength prediction method for the broadcasting service in the frequency range 150–1600 kHz Note-Suppressed on 20/10/95 (RA-95)
P.452*	Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz
P.453*	The radio refractive index: its formula and refractivity data Note-This Recommendation replaces Rec. ITU-R P.369-6

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Radiowave Propagation	
P.525	Calculation of free-space attenuation
P.526	Propagation by diffraction draft revision P.526-9(08/05)
P.527	Electrical characteristics of the surface of the Earth
P.528	Propagation curves for aeronautical mobile and radio navigation services using the VHF, UHF, and SHF bands
P.529	Prediction methods for the terrestrial land mobile service in the VHF and UHF bands Note-Suppressed on 22/10/01 (CACE/233)
P.530*	Propagation data and prediction methods required for the design of terrestrial line-of-sight systems
P.531	Ionospheric propagation data and prediction methods required for the design of satellite services and systems
P.532	Ionospheric effects and operational considerations associated with artificial modification of the ionosphere and the radio-wave channel
P.533*	HF propagation prediction method
P.534	Method for calculating sporadic-E field strength
P.581	The concept of “worst month”
P.616	Propagation data for terrestrial maritime mobile services operating at frequencies above 30 MHz. Note-Suppressed on 22/10/01 (CACE/233)
P.617	Propagation prediction techniques and data required for the design of trans-horizon radio-relay systems
P.618*	Propagation data and prediction methods required for the design of Earth-space telecommunication systems
P.619	Propagation data required for the evaluation of interference between stations in space and those on the surface of the Earth
P.620	Propagation data required for the evaluation of coordination distances in the frequency range 100 MHz to 105 GHz
P.676	Attenuation by atmospheric gases
P.678*	Characterization of the natural variability of propagation phenomena
P.679*	Propagation data required for the design of broadcasting satellite systems
P.680	Propagation data required for the design of Earth-space maritime mobile telecommunication systems

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Radiowave Propagation	
P.681*	Propagation data required for the design of Earth-space land mobile telecommunication systems
P.682	Propagation data required for the design of Earth-space aeronautical mobile telecommunication systems
P.683	Sky wave field strength prediction method for propagation to aircraft at about 500 kHz. Note-Suppressed on 20/10/95 (RA-95)
P.684	Prediction of field strength at frequencies below about 150 kHz
P.832*	World Atlas of Ground Conductivities
P.833	Attenuation in vegetation. Draft revision P.833-5(08/05)
P.834	Effects of tropospheric refraction on radiowave propagation
P.835	Reference Standard Atmospheres
P.836	Water vapor: surface density and total columnar content
P.837	Characteristics of precipitation for propagation modeling
P.838	Specific attenuation model for rain for use in prediction methods
P.839	Rain height model for prediction methods
P.840	Attenuation due to clouds and fog
P.841	Conversion of annual statistics to worst-month statistics
P.842	Computation of reliability and compatibility of HF radio systems
P.843	Communication by meteor burst propagation
P.844	Ionospheric factors affecting frequency sharing in the VHF and UHF bands (30 MHz to 3 GHz)
P.845	HF field strength measurement
P.846	Measurements of ionospheric and related characteristics
P.1057*	Probability distributions relevant to radiowave propagation modeling
P.1058	Digital topographic databases for propagation studies
P.1059	Method for predicting sky wave field strengths in the frequency range 1605–1705 kHz. Note-Suppressed on 20/10/95 (RA-95)
P.1060	Propagation factors affecting frequency sharing in HF terrestrial systems

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Radiowave Propagation	
P.1144*	Guide to the application of the propagation methods of Radiocommunication Study Group 3
P.1145	Propagation data for the terrestrial land mobile service in the VHF and UHF bands Note-Suppressed
P.1146	The prediction of field strength for land mobile and terrestrial broadcasting services in the frequency range from 1 to 3 GHz. Note-Suppressed on 22/10/01 (CACE/233)
P.1147	Prediction of sky-wave field strength at frequencies between about 150 and 1700 kHz
P.1148	Standardized procedure for comparing predicted and observed HF sky wave signal intensities and the presentation of such comparisons
P.1238*	Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz
P.1239	ITU-R reference ionospheric characteristics
P.1240*	ITU-R methods of basic MUF, operational MUF, and ray path prediction
P.1321*	Propagation factors affecting systems using digital modulation techniques at LF and MF
P.1322	Radiometric estimation of atmospheric attenuation
P.1406*	Propagation effects relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands
P.1407	Draft revision of recommendation ITU-R P.1407-1. Multipath propagation and parameterization of its characteristics
P.1409	Propagation data and prediction methods required for the design of systems using high-altitude platform stations at about 47 GHz
P.1410	Propagation data and prediction methods required for the design of terrestrial broadband millimetric radio access systems operating in a frequency range of about 20–50 GHz
P.1411*	Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz

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Radiowave Propagation	
P.1412	Propagation data for the evaluation of coordination between Earth stations working in the bidirectionally allocated frequency bands
P.1510	Annual mean surface temperature
P.1511*	Topography for Earth-to-space propagation modeling
P.1546	Method for point-to-area predictions for terrestrial services in the frequency range 30–3000 MHz. Draft revision P.1546-2(08/05)
P.1621*	Propagation data required for the design of Earth-space systems operating between 20 and 375 THz
P.1622	Prediction methods required for the design of Earth-space systems operating between 20 and 375 THz
P.1623	Prediction method of fade dynamics on Earth-space paths
P.1791	Propagation prediction methods for assessment of the impact of ultra-wideband devices
P.1812*	A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands
P.1814	Prediction methods required for the design of terrestrial free-space optical links
P.1815	Differential rain attenuation
P.1816*	The prediction of the time and the spatial profile for broadband land mobile services using UHF and SHF bands
P.1817	Propagation data required for the design of terrestrial free-space optical links
P.2001**	A general-purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz
P.2040**	Effects of building materials and structures on radiowave propagation above about 100 MHz

1. Recommendations marked by * have been revised by ITU-R in 2015.
2. Recommendations marked by ** are new ones.

Appendix C
ITU-R-Based Terms and Definitions Related to Propagation in Non-ionized Media (P-310)

The ITU Radiocommunication Assembly,
considering

(a) that it is important to have agreed definitions of propagation terms used in the texts of ITU-R Study Groups,

recommends

1. that the list of definitions annexed hereto be adopted for incorporation in the vocabulary.

C.1 Vocabulary of Terms Used in Radio Propagation in Non-ionized Media

	Term	Definition
A.	Terms related to radiowaves	
A1.	Cross-polarization	The appearance, in the course of propagation, of a polarization component which is orthogonal to the expected polarization.
A2.	Cross-polarization discrimination	For a radiowave transmitted with a given polarization, the ratio at the reception of the power received with the expected polarization to the power received with the orthogonal polarization. Note 1—The cross-polarization discrimination depends both on the characteristics of the antenna and on the propagation medium.

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A3.	Cross-polarization isolation	For two radiowaves transmitted with the same frequency with the same power and orthogonal polarization, the ratio of the co-polarized power in a given receiver to the cross-polarized power in that receiver.
A4.	Depolarization	A phenomenon by virtue of which all or part of the power of a radiowave transmitted with a defined polarization may no longer have a defined polarization after propagation.
B.	Terms related to ground effects on radiowave propagation	
B1.	Free-space propagation	Propagation of an electromagnetic wave in a homogeneous ideal dielectric medium which may be considered of infinite extent in all directions.
B2.	Line-of-sight propagation	Propagation between two points for which the direct ray is sufficiently clear of obstacles for diffraction to be of negligible effect.
B3.	Radio horizon	The locus of points at which direct rays from a point source of radiowaves are tangential to the surface of the Earth. Note 1—As a general rule, the radio and geometric horizons are different because of atmospheric refraction.
B4.	Penetration depth	The depth within the Earth at which the amplitude of a radiowave incident at the surface falls to a value $1/e$ (0.368) of its value at the surface.
B5.	Smooth surface; specular surface	A surface separating two media which is sufficiently large and the irregularities of which are sufficiently small to cause specular reflection. Note 1—In practice, the minimum size of the surface corresponds to the first Fresnel zone and the importance of irregularities is estimated using the Rayleigh criterion.
B6.	Rough surface	A surface separating two media which does not fulfill the smooth surface conditions and the irregularities of which are randomly located and cause diffuse reflection.
B7.	Diffuse reflection coefficient	The ratio of the amplitude of the incoherent wave reflected from a rough surface to the amplitude of the incident wave.
B8.	Measure of terrain irregularity; Δh	A statistical parameter which characterizes the variations in ground height along part or all of a propagation path. Note 1—For example, Δh is often defined as the difference between the heights exceeded by 10 and 90 %, respectively of the terrain heights measured at regular intervals (the interdecile height range) along a specified section of a path.
B9.	Obstacle gain	The enhancement in field strength, which can occur at one end of a transmission path including an isolated obstacle, with respect to the field strength which would occur at the same point if this obstacle was removed.

B10.	Site shielding	The reduction in the level of interference radio signals reaching an antenna situated near the ground, due to natural or artificial obstacles in the vicinity of the antenna.
B11.	Site shielding factor	The ratio, generally expressed in dB, of the level of an interfering radio signal which would occur without any site shielding to the actual level of the interfering radio signal with site shielding.

C. Terms related to tropospheric effects on radiowave propagation

C1.	Troposphere	The lower part of the Earth atmosphere extending upward from the Earth's surface, in which temperature decreases with height except in local layers of temperature inversion. This part of the atmosphere extends to an altitude of about 9 km at the Earth's poles and 17 km at the equator.
C2.	Temperature inversion (in the troposphere)	An increase in temperature with height in the troposphere.
C3.	Mixing ratio	The ratio of the mass of water vapor to the mass of dry air in a given volume of air (generally expressed in g/kg).
C4.	Refractive index; n	Ratio of the speed of radiowaves in vacuo to the speed in the medium under consideration.
C5.	Refractivity; N	One million times the amount by which the refractive index n in the atmosphere exceeds unity: $N = (n - 1)10^6$
C6.	N-unit	A dimensionless unit in terms of which refractivity is expressed.
C7.	Modified refractive index	The sum of the refractive index n of the air at height h and the ratio of this height to the radius of the Earth, a: $n = \frac{h}{a}$
C8.	Refractive modulus;	One million times the amount by which the modified refractive index exceeds unity: $M = (n + \frac{h}{a} - 1)10^6 = N + 10^6\frac{h}{a}$
C9.	M-unit	A dimensionless unit in terms of which refractive modulus M is expressed.
C10.	Standard refractivity gradient	A standard value of vertical gradient of refractivity used in refraction studies, namely, −40 N/km. This corresponds approximately to the median value of the gradient in the first kilometer of altitude in temperate regions.
C11.	Standard radio atmosphere	An atmosphere having the standard refractivity gradient.
C12.	Reference atmosphere for refraction	An atmosphere in which $n(h)$ decreases with height as given in Recommendation ITU-R P.453.
C13.	Sub-refraction	Refraction for which the refractivity gradient is greater (i.e., positive or less negative) than the standard refractivity gradient.

C14.	Super refraction	Refraction for which the refractivity gradient is less (i.e., more negative) than the standard refractivity gradient.
C15.	Effective radius of the Earth	Radius of a hypothetical spherical Earth, without atmosphere, for which propagation paths are along straight lines, the heights and ground distances being the same as for the actual Earth in an atmosphere with a constant vertical gradient of refractivity. Note 1—The concept of effective radius of the Earth implies that the angles with the horizontal planes made at all points by the transmission paths are not too large. Note 2—For an atmosphere having a standard refractivity gradient, the effective radius of the Earth is about 4/3 that of the actual radius, which corresponds to approximately 8500 km.
C16.	Effective Earth radius factor, k	Ratio of the effective radius of the Earth to the actual Earth radius. Note 1—This factor k is related to the vertical gradient dn/dh of the refractive index n and to the actual Earth radius a by the equation: $k = \frac{1}{1+a\frac{dn}{dh}}$
C17.	Ducting layer	A tropospheric layer characterized by a negative M gradient, which consequently may generate a tropospheric radio duct if the layer is sufficiently thick compared with the wavelength.
C18.	Tropospheric radio duct	A quasi-horizontal stratification in the troposphere within which radio energy of a sufficiently high frequency is substantially confined and propagates with much lower attenuation than would be obtained in a homogeneous atmosphere. Note 1—The tropospheric radio duct consists of a ducting layer and, in the case of an elevated duct, the portion of the underlying atmosphere in which the refractive modulus exceeds the minimum value attained in the ducting layer.
C19.	Ground-based duct (surface duct)	A tropospheric radio duct in which the lower boundary is the surface of the Earth.
C20.	Elevated duct	A tropospheric radio duct in which the lower boundary is above the surface of the Earth.
C21.	Duct thickness	The difference in height between the upper and lower boundaries of a tropospheric radio duct.
C22.	Duct height	The height above the surface of the Earth of the lower boundary of an elevated duct.
C23.	Duct intensity	The difference between the maximum and minimum values of the refractive modulus in a tropospheric radio duct. Note 1—The intensity of a duct is the same as that of its ducting layer.

C24.	Ducting	Guided propagation of radiowaves inside a tropospheric radioduct. Note 1—At sufficiently high frequencies, a number of electromagnetic modes of guided propagation can coexist in the same tropospheric radio duct.
C25.	Trans-horizon propagation	Tropospheric propagation between points close to the ground, the reception point being beyond the radio horizon of the transmission point. Note 1—Trans-horizon propagation may be due to a variety of tropospheric mechanisms such as diffraction, scattering, and reflection from tropospheric layers. However, ducting is not included because in a duct there is no radio horizon.
C26.	Tropospheric-scatter propagation	Tropospheric propagation due to scattering from many inhomogeneities and discontinuities in the refractive index of the atmosphere.
C27.	Hydrometeors	Concentrations of water or ice particles which may exist in the atmosphere or be deposited on the surface of the Earth. Note 1—Rain, fog, clouds, snow, and hail are the main hydrometeors.
C28.	Aerosols	Small particles in the atmosphere (other than fog or cloud droplets) which do not fall rapidly under gravity.
C29.	Precipitation-scatter propagation	Tropospheric propagation due to scattering caused by hydrometeors, mainly rain.
C30.	Multipath propagation	Propagation of the same radio signal between a transmission point and a reception point over a number of separate propagation paths.
C31.	Scintillation	Rapid and random fluctuation in one or more of the characteristics (amplitude, phase, polarization, direction of arrival) of a received signal, caused by refractive index fluctuations of the transmission medium.
C32.	Gain degradation; antenna to medium coupling loss	The apparent decrease in the sum of the gains (expressed in decibels) of the transmitting and receiving antennas when significant scattering effects occur on the propagation path.
C33.	Precipitation rate; rainfall rate; rain rate	A measure of the intensity of precipitation expressed by the increase in the height of water reaching the ground per unit time. Note 1—Rain rate is generally expressed in millimeters per hour.

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⁎ Softwares

[1] GIMS-Graphical Interference Management
[2] SpaceCap-Space Data Capture on PC
[3] SpaceCom-Space Comment Capture on PC
[4] SpacePub-Space Publication
[5] SpaceQry-Space Query and Extract System
[6] SpaceVal-Space Filings Validation Software
[7] SNS-Space Network Systems
[8] Electronic Submission of Graphical Data
[9] SRS-Database Conversion Utility
[10] SRS-Fix Electronic Notification Database Utility
[11] SRS-Space Radio Communications Stations on CD-ROM
[12] SNL-Space Network List
[13] Global Administration Data (GLAD)
[14] Maritime Mobile Access and Retrieval System (MARS)
[15] HFBC Planning Software
[16] FXM Data Capture

[17] TstTrs Attention to the File Size
[18] Interference Calculations GE84 Attention to the File Size
[19] Interference Calculations GE89 Attention to the File Size
[20] SG 1-Programs on Spectrum Management
[21] SG 3-Databanks and Computer Programs on Radiowave Propagation
[22] SG 4-Databanks (Currently in Development)
[23] ITU Patent Statement and Licensing Declaration Information
[24] Ground-wave Propagation (GRWAVE)
[25] UTD Formulation for Diffraction Loss due to Finitely Conducting Wedge
[26] Point-to-area Prediction, 30–3000 MHz
[27] Point-to-point (Interference) Propagation
[28] Rain Scatter (SCAT)
[29] Radio Refractivity
[30] Atmospheric Gaseous Absorption
[31] Atmospheric Profile Data
[32] Water Vapor Data
[33] Rainfall Rate Model
[34] Specific Attenuation Model for Rain
[35] Rain Height Model
[36] Cloud Liquid Water Data
[37] Annual Mean Surface Temperature
[38] Topography (0.50 Resolution)
[39] K9SE: VHF and UHF Propagation www.dxzone.
[40] W6EL Prop: Predict Ionospheric (Sky-wave) Propagation (3–30 MHz) www.qsl.net/w6elprop
[41] TAP: Terrain Analysis Package www.softwright.com
[42] PA 3CQR Gray Line www.iri.tudelft.nl
[43] HF Software www.elbert.its.bldrdoc.gov
[44] WinCAP Wizard 3 www.taborsoft.com
[45] Win BASMS www.winpath.com
[46] Win BASMS www.itu.int

⁎ Web Sites

[1] INMARSAT www.inmarsat.com and www.Inmarsat.org
[2] EUTELSAT www.eutelsat.org
[3] INTELSAT www.intelsat.com
[4] METEOSAT www.meteosat.com
[5] IEC www.iec.ch and www.iec.org
[6] ISO www.iso.ch
[7] EIA www.eia.org
[8] BTS www.bt.com
[9] ITU www.itu.int

[10] ETSI www.etsi.org
[11] ASTM www.astm.org
[12] WMO www.wmo.ch
[13] IEEE www.ieee.org, www.ieeexplore.ieee.org
[14] IEE www.iee.org
[15] IMO www.imo.org
[16] ICAO www.icao.int

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