THE LTE-ADVANCED DEPLOYMENT HANDBOOK

THE LTE-ADVANCED DEPLOYMENT HANDBOOK

THE PLANNING GUIDELINES FOR THE FOURTH GENERATION NETWORKS

Edited by

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Preface

Mobile communications technologies are developing in giant leaps especially in the current LTE era. The initial phase of the enhanced 3G system driven by 3GPP resulted in LTE/SAE, as defined in Release 8. It has already opened doors for a much more fluent user experience, thanks to the considerably higher data rates and lower response times compared to any other previous cellular system. The first LTE deployments took place in 2010–11, and the pace has been breathtaking ever since. According to 4G Americas (www.4gamericas.org), there were 755 Million LTE subscribers by June 2015, which proves there is high demand for mobile data.

Further development has resulted in the 3GPP Release 10 standards which represent the first set for the LTE-Advanced (LTE-A) system. The ITU (International Telecommunications Union) has defined demanding criteria for the use of the term 4G, including requirements for the capability of the mobile network to transfer a minimum of 1 Gb/s data rate in the downlink. 3GPP LTE in Release 10 starts to include enough components that jointly contribute to the total performance so efficiently that it can already be called an ITU-compliant 4G system. In practice, the term 4G has been used already for some time to distinguish even between basic LTE and the previous 3G variants. This market interpretation is of course justified as the LTE as such opens the door to the next generation via the gradual upgrading of the network and user device functionalities. Nevertheless, in this book, the term 4G refers to the 3GPP LTE Release 10 and beyond, while earlier LTE variants in Release 8 and 9 are referred to in this book as "evolved 3G, or pre-4G" systems.

At the time of writing, there have already been 32 LTE-Advanced networks in 23 countries by the end of 2014, according to 4G Americas. The deployments are still expanding so it can be expected that Release 10 and beyond networks will be widely available for we mobile users to enjoy fluent connectivity and to consume high-quality multimedia contents globally easier than ever.

Observing all the accelerating developments of mobile communications technologies, it is in fact almost impossible to keep track of the advances even in real-time web discussion forums. Nevertheless, I believe it is totally justified to summarize technical areas in a single package, as *The LTE-Advanced Deployment Handbook* aims to do, to aid studies in capturing the complete picture and the key set of relevant details. Even with the further advances beyond this book contents, the basics described here will be an important building block for the investigations of the next releases. As an additional aim to ensure the contents of this book are up to date, there also are updates provided in www.tlt.fi which collects further key data and useful information about the development of LTE and LTE-Advanced systems.

This book is the result of innumerable hours of work by the team, and there are many highly relevant real-world experiences behind each chapter. I hope our creation of this information package on LTE-Advanced principles, functionality and planning has been worth the effort and you will find it useful in your studies and work. As was the case with the previous *LTE/SAE Deployment Handbook*, published by Wiley in 2011, I would be glad to receive your valuable feedback about this book directly via my e-mail address jyrki.penttinen@hotmail.com.

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Acknowledgments

The LTE-Advanced Deployment Handbook is a follow-on to the previously published *LTE/SAE Deployment Handbook* which describes key aspects of the initial LTE phase. This *LTE-Advanced Deployment Handbook* details the now essential functionality of the system and provides planning guidelines for the developed phase of LTE in Release 10 and beyond.

This book is the result of our contributor team's efforts as well as our collaboration with many LTE subject matter experts and seasoned professionals. I would like to thank the whole team and the participating colleagues for the most valuable information sharing and contribution, often sacrificing their precious private time. I know that the team has succeeded excellently in our mission to provide an up-to-date, practical and useful guide for both academic as well as operational LTE-Advanced environments.

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Jyrki Penttinen

Abbreviations

2G	Second Generation of mobile communication technologies
3G	Third Generation of mobile communication technologies
3GPP	3rd Generation Partnership Project
4G	Fourth Generation of mobile communication technologies
16-QAM	16-state Quadrature Amplitude Modulation
64-QAM	64-state Quadrature Amplitude Modulation
AAA	Authentication, Authorization & Accounting
AAS	Active/Adaptive Antenna System
ABS	Almost Blank Subframes
AC	Admission Control
ACIR	Adjacent Channel Interference Rejection
ACK	Acknowledgment
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
ACS	Advanced Communications Services
ADC	Analogue/Digital Conversion
ADSL	Asynchronous Digital Subscriber Line
AF	Application Function
A-GNSS	Assisted Global Navigation Satellite System
aGW	Access Gateway
AKA	Authentication and Key Agreement
AMBR	Aggregated Maximum Bit Rate
AMC	Adaptive Modulation and Coding
ANDSF	Access Network Discovery and Selection Function
ANR	Automatic Neighbor Relation
AoA	Angle of Arrival
APAC	Asia Pacific, Africa and China
APN	Access Point Name
ARFCN	Absolute Radio Frequency Channel Number
ARP	Allocation Retention Priority
ARPU	Average Revenue Per User
ARQ	Automatic Repeat request
AS	Application Server
ATB	Adaptive Transmission Bandwidth

ATCF	Access Transfer Control Function
ATGW	Access Transfer Gateway Function
ATM	Asynchronous Transfer Mode
AWS	Advanced Wireless Services (band)
BBIC	Baseband Integrated Circuit
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BE	Best Effort
BER	Bit Error Rate
BICC	Bearer Independent Call Control
BIP	Bearer Independent Protocol
BLEP	Block Error Probability
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
BQS	Bad Quality Sample
BS	Base Station
BSC	Base Station Controller
BSR	Buffer Status Report
BSS	Business Support System
BTS	Base Transceiver Station
BW	Bandwidth
CA	Carrier Aggregation
CAMEL	Customised Applications for Mobile networks Enhanced Logic
CAPEX	Capital Expenditure
CAT	Category (user equipment)
CAZAC	Constant Amplitude Zero AutoCorrelation
CB	Coordinated Beam forming
CC	Component Carrier
CCCH	Common Control Channel
CCN	Cell Change Notification
CCO	Cell Change Order
CCO	Coverage and Capacity Optimization
CDMA	Code Division Multiple Access
CDP	Charging Downstream Port
CDR	Call Drop Rate
CDR	Charging Data Record
CDR	Clock Drift Ratio
CES	Circuit Emulated Services
CET	Carrier Ethernet Transport
C/I	Carrier per Interference
CIO	Cell Individual Offset
CLF	Contactless Frontend
CMAS	Commercial Mobile Alert System
CN	Core Network
CoMP	Coordinated Multipoint
CoS	Class of Service
CP	Cyclic Prefix

CPE	Customer Premises Equipment
CPICH	Common Pilot Channel
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CRE	Cell Range Expansion
CS	Circuit Switched
CS	Coordinated Scheduling
CSFB	Circuit Switched Fall Back
CSI	Channel State Information
CT	Core Network and Terminals (TSG)
CTIA	Cellular Telecommunications and Internet Association
CVAA	Communications and Video Accessibility Act
DAB	Digital Audio Broadcasting
DCCH	Dedicated Control Channel
DCP	Dedicated Charging Port
DCR	Dropped Call Rate
DCS	Dynamic Cell Selection
DD	Digital Dividend
DDoS	Distributed DoS
DeNodeB	Donor eNodeB element
DFCA	Dynamic Frequency and Channel Allocation
DFT	Discrete Fourier Transform
DFTS-OFDM	Discrete Fourier Transform Spread-OFDM
DHR	Dual Half Rate (voice codec)
DL	Downlink
DLDC	Downlink Dual Carrier
DL-SCH	Downlink Shared Channel
DMRS	Demodulation Reference Symbol
DM-RS	Demodulation Reference Signal
DoS	Denial of Service
DPI	Deep Packet Inspection
DRS	Dedicated Reference Symbol
DRX	Discontinuous Reception
DSCP	DiffServ Code Point
DSL	Digital Subscriber Line
DSMIPv6	Dual-Stack Mobile IPv6
DTM	Dual Transfer Mode
DTMF	Dual Tone Multi-Frequency
DTX	Discontinuous Transmission
DUT	Device Under Test
DVB-H	Digital Video Broadcasting, Handheld
DVB-T	Digital Video Broadcasting, Terrestrial
DwPTS	Downlink Pilot Timeslot
eBM-SC	Evolved Broadcast/Multicast Service Center
E-CID	Enhanced Cell ID
ECM	EPS Connection Management
E-CSCF	Emergency Call State Control Function

EDGE	Enhanced Data Rates for Global Evolution
EFL	Effective Frequency Load
EGAN	Enhanced GAN
EHPLMN	Equivalent HPLMN
eHRPD	Evolved High Rate Packet Data
eICIC	Enhanced Inter-Cell Interference Coordination
EIRP	Effective Isotropic Radiating Power
eMBMS	Evolved MBMS
EMM	EPS Mobility Management
EMR	Enhanced Measurement Reporting
eNB	Evolved NodeB
EOL	End of Life (product phase)
EPC	Evolved Packet Core
ePDG	Evolved Packet Data Gateway
EPS	Evolved Packet System
ERP	Effective Radiated Power
eSE	Embedded Secure Element
E-SMLC	Enhanced Serving Mobile Location Centre
ET	Envelope Tracking
ETSI	European Telecommunications Standards Institute
ETWS	Earthquake and Tsunami Warning System
E-UTRAN	Evolved UMTS Radio Access Network
EV-DO	Evolution-Data Only
EVM	Error Vector Magnitude
FACCH	Fast Associated Control Channel
FCC	Federal Communications Commission (USA)
FCCH	Frequency Correction Channel
FDD	Frequency Division Duplex
FDPS	Frequency-Domain Packet Scheduling
FER	Frame Erasure Rate
FF	Form Factor
FFS	For Further Study
FFT	Fast Fourier Transform
FH	Frequency Hopping
FM	Fault Management
FOMA	Freedom of Mobile Multimedia Access
FR	Frame Relay
FR	Full Rate (voice codec)
FR-AMR	AMR Full Rate
GAN	Generic Access Network
GBR	Guaranteed Bit Rate
GCF	Global Certification Forum
GERAN	GSM EDGE Radio Access Network (TSG)
GGSN	GPRS Gateway Support Node
GMLC	Gateway Mobile Location Centre
GMM	GPRS Mobility Management
GMSK	Gaussian Minimum Shift Keying

GoS	Grade of Service
GP	Guard Period
GPRS	General Packet Radio Service
GRE	Generic Routing Encapsulation
GRX	GPRS Roaming Exchange
GSM	Global System for Mobile communications
GSMA	GSM Association
GTP	GPRS Tunnelling Protocol
GTT	Global Text Telephony
GTT-CS	Global Text Telephony over video telephony
GTTP	GPRS Transparent Transport Protocol
GTT-Voice	Global Text Telephony over voice
GW	Gateway
HARQ	Hybrid Automatic Retransmission on request/Hybrid Automatic Repeat Request
HD	High Definition
HDSL	High-bit-rate Digital Subscriber Line
HeNB	Home eNB
HLR	Home Location Register
HO	Handover
hPCRF	Home Policy and Charging Rules Function
HPLMN	Home PLMN
HR	Half Rate (voice codec)
HR-AMR	AMR Half Rate
HRPD	High Rate Packet Data
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
HSUPA	High Speed Uplink Packet Access
ICI	Inter-Carrier Interference
ICIC	Inter Cell Interference Control
ICS	IMS Centralized Services
I-CSCF	Interrogating Call State Control Function
IDFT	Inverse Discrete Fourier Transform
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
I-HSPA	Internet HSPA
IMEI	International Mobile Equipment Identity
IMS	IP Multimedia Sub-system
IMSI	International Mobile Subscriber Identity
IMS-MGW	IMS-Media Gateway
IMS-NNI	IMS Network-Network Interface
IM-SSF	IP Multimedia – Service Switching Function
IMT-2000	International Mobile Telecommunication requirements (ITU)

IMT-Advanced	Advanced International Mobile Telecommunication requirements (ITU)
IN	Intelligent Network
INAP	Intelligent Network Application Protocol
IoT	Internet of Things
IOT	Inter-Operability Testing
IP	Internet Protocol
IPSec	IP Security
IP-SM-GW	IP-Short Message-Gateway
IPv4	IP version 4
IPv6	IP version 6
IPX	IP eXchange
IPXS	IP interconnection of services
IQ	In-phase (I) and out of phase (Q) components of modulation
IRC	Interference Rejection Combining
ISI	Inter-Symbol Interference
ISIM	IMS Subscriber Identity Module
ISR	Idle Mode Signalling Reduction
ISUP	ISDN User Part
ITU	International Telecommunication Union
ITU-R	ITU's Radiocommunication Sector
ITU-T	ITU's Telecommunication sector
JAIN	Java APIs for Integrated Networks
JP	Joint Processing
JSLEE	JAIN Service Logic Execution Environments
JT	Joint Transmission
KPI	Key Performance Indicator
LA	Link Adaptation
LA	Location Area
LAU	Location Area Update
LBO	Local Breakout
LBS	Location Based Service
LCS	Location Service
LI	Lawful/Legal Interception
LIG	Legal Interception Gateway
LIPA	Local IP Access
LNF	Log Normal Fading (margin)
LPP	LTE Positioning Protocol
LPPa	LPP annex
LRF	Location Retrieval Function
LSP	Label Switch Path
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LTE-UE	LTE User Equipment
MA	Mobile Allocation
MAC	Medium Access Control
MAIO	Mobile Allocation Index Offset
MAN	Metropolitan Area Network

MBI	MIMO Band Index
MBMS	Multimedia Broadcast Multicast Service
MBR	Maximum Bit Rate
MBSFN	MBMS Single Frequency Network area
MCC	Mobile Country Code
MCCH	Multicast Control Channel
MCE	Multi-cell/multicast Coordination Entity
MCH	Multicast Channel
MCS	Modulation and Coding Scheme
MC-TD-SCDMA	Multi-Carrier Time-Division Synchronous-Code-Division Multiple Access
MC-WCDMA	Multi-Carrier Wide-band Code-Division Multiple Access
MDT	Minimization of Drive Tests
ME id	Mobile Equipment Identifier
MEG	Mean Effective Gain
MER	Modulation Error Rate
MGCF	Media Gateway Control Function
MGW	Media Gateway
MHA	Mast Head Amplifier
MIMO	Multiple Input Multiple Output
MM	Mobility Management
MME	Mobility Management Entity
MMS	Multimedia Messaging Service
MMTel	Multimedia Telephony
MNC	Mobile Network Code
MO	Mobile Originating (call)
MOBSS	Multi-Operator Base Station Subsystem
MOCN	Multi-Operator Core Network
MORAN	Multi-Operator Radio Access Network
MOS	Mean Opinion Score
MPLS	Multi-Protocol Label Switching
MRF	Media Resource Function
MRFC	Media Resource Function Controller
MRFP	Media Resource Function Processor
MRM	Measurement Report Message
MRO	Mobility Robustness/handover Optimization
MS	Mobile Station
MSC	Mobile services Switching Center
MSC-B	Second MSC
MSISDN	Mobile Station ISDN number
MT	Mobile Terminating (call)
MTCH	Multicast Traffic Channel
MT-LR	Mobile Terminating Location Request
MTM	Machine-to-Machine (communications); also M2M
MVNO	Mobile Virtual Network Operator
NA	Network Assisted
NACC	Network Assisted Cell Change
NACK	Negative Acknowledgment

NAS	Non Access Stratum
NAS SMC	NAS Security Mode Command
NB	Node B
NBC	Non-Backwards Compatible
NCCR	Network Controlled Cell Reselection
NDS	Network Domain Security
NE	Network Element
NE Id	Network Element Identifier
NFC	Near Field Communications
NGMN	Next Generation Mobile Networks (Alliance)
NGN	Next Generation Network
NH	Next Hop (parameter)
NITZ	Network Initiated Time Zone
NNI	Network-Network Interface
NOC	Network Operations Centre
NRT	Near Real Time
NVAS	Network Value Added Services
OAM&P	Operations, Administration, Maintenance, and Provisioning
OEM	Original Equipment Manufacturer
OFDMA	Orthogonal Frequency Division Multiple Access
OLLA	Outer Loop Link Adaptation
OLPC	Open Loop Power Control
OMS	Operations and Management System
OPEX	Operating Expenditure
OSC	Orthogonal Sub Channel
OSPIH	Internet Hosted Octect Stream Protocol
OSS	Operational Support System
OTA	Over the Air
OTDOA	Observed Time Difference of Arrival
OTT	Over the Top
P2P	Peer-to-Peer
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PAS	Power Azimuth Spectrum
PBCH	Physical Broadcast Channel
PBR	Prioritized Bit Rate
PBX	Private Branch Exchange
PC	Power Control
PCC	Policy and Charging Control
PCC	Primary Component Carrier
PCCH	Paging Control Channel
PCEF	Policy and Charging Enforcement Function
PCEP	Policy and Charging Enforcement Point
PCH	Paging Channel
PCI	Physical Cell Identifier
PCRF	Policy and Charging Rules Function
P-CSCF	Proxy Call State Control Function

PD	Packet delay
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDH	Plesiochronous Digital Hierarchy
PDN	Packet Data Network
PDN-GW	Packet Data Network Gateway
PDP	Packet Data Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PDV	Packet Delay Variation
P-GW	Packet Data Network Gateway
PHB	Per Hop Behavior (DiffServ)
PHICH	Physical Hybrid ARQ Indicator Channel
PHR	Power Headroom Report
PKI	Public Key Infrastructure
PLMN	Public Land Mobile Network
PLR	Packet Loss Ratio
PM	Performance Monitoring
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
PMIP	Proxy Mobile IP
PMIPv6	Proxy Mobile IP version 6
PPP	Point to Point Protocol
PRACH	Physical Radio Access Channel
PRB	Physical Resource Block
PS	Packet Switched
PS	Presence Server
PSAP	Public Safety Answering Point
PSD	Packet Switched Data
PSN	Packet Switched Network
PTCRB	PCS Type Certification Review Board
PTP	Point-to-Point
PUSCH	Physical Uplink Shared Channel
PWS	Public Warning System
Q	Quality
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Routing Area
RACH	Random Access Channel
RAN	Radio Access Network (TSG)
RAND	Random challenge number
RAT	Radio Access Technology
RAU	Routing Area Update
RB	Resource Block

RBG	Radio Bearer Group
RCS	Rich Communication Suite
RES	Response
RF	Radio Frequency
RF	Rating Function
RFSP	RAT/Frequency Selection Priority
RI	Rank Indicator
RLC	Radio Link Control
RLF	Radio Link Failure
RLT	Radio Link Timeout
RMS	Root Mean Square
RN	Relay Node
ROHC	Robust Header Compression
RoI	Return of Investment
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RRU	Remote Radio Unit
RS	Reference Signal
RSCP	Received Signal Code Power
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
rSRVCC	Reverse SRVCC
RSSI	Received Signal Strength Indicator
RT	Real Time
RTCP	RTP Control Protocol
RTG	Receive-to-transmit Transition Gap
RTP	Real Time Transport Protocol
RX	Receiver
RX-D	Diversity Receiver
RXLEV	Received Level
RXQUAL	Received Quality
SA	Service and System Aspects (TSG)
SACCH	Slow Associated Control Channel
SAE	System Architecture Evolution
SAE-GW	Combined S-GW and P-GW
SAIC	Single Antenna Interference Cancellation
SAR	Specific Absorption Rate
SAU	Simultaneously Attached Users
SBC	Session Border Controller
SCC	Secondary Component Carrier
SCC AS	Service Centralization and Continuity Application Server
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCH	Shared Channel
SCIM	Service Control Interaction Management
SCP	Service Control Point
S-CSCF	Serving Call State Control Function

SCTP	Stream Control Transfer Protocol
SDCCH	Stand-alone Dedicated Control Channel
SDF	Service Delivery Framework
SDH	Synchronous Digital Hierarchy
SDP	Session Description Protocol
SE	Secure Element
SEG	Security Gateway
SeGW	Security Gateway
SEL	Spectral Efficiency Loss
SEM	Spectral Emission Mask
SFN	Single Frequency Network
SFP	Small Form Factor Pluggable
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SIB	System Information Block
SIM	Subscriber Identity Module
SIMTC	System improvements to machine-type communications
SINR	Signal-to-Interference-and-Noise Ratio
SIP	Session Initiation Protocol
SIPTO	Selected Internet IP Traffic Offload
SISO	Single Input Single Output
SLA	Service Level Agreement
SLF	Subscriber Locator Function
SM	Short Message
SMC	Security Mode Command
SMG	Special Mobile Group
SMI	Spatial Multiplexing Index
SMS	Short Message Service
SMSC	Short Message Service Centre
SN ID	Serving Network's Identity
SNR	Signal-to-Noise Ratio
SON	Self Organizing/Optimizing Network
S/P-GW	Serving Gateway and PDN Gateway (combined)
SR	Scheduling Request
SRS	Sounding Reference Signal
SRVCC	Single Radio Voice Call Continuity
SS	Signal Strength
SSC	Special Subframe Configuration
STM	Synchronous Transfer Mode
SU-MIMO	Single User MIMO
SUPL	Secure User Plane Location
SWP	Single Wire Protocol
SWR	Standing Wave Ratio
TA	Tracking Area
T-ADS	Terminating Access Domain Selection
TAS	Telephony Application Server
TAU	Tracking Area Update

TBF	Temporary Block Flow
TBS	Transport Block Size
TCH	Traffic Channel
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplex
TDM	Time Domain
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TEID	Tunnel Endpoint Identifier
TFO	Tandem-Free Operation
THIG	Topology Hiding
TM	Transmission Mode
TMA	Tower Mounted Amplifier
TMSI	Temporary Mobile Subscriber Identity
TN-SR	Transfer Number for Single Radio
ToP	Timing over Packet
TR	Technical Recommendation
TrFO	Transcoder Free Operation
TrGW	Transition Gateway
TRP	Transmitter Radiating Power
TRX	Transceiver
TS	Technical Specification
TSG	Technical Specification Group
TSL	Timeslot
TTCN3	Testing and Test Control Notation Version 3
TTG	Transmit-to-receive Transition Gap
TTI	Transmission Time Interval
TU3	Typical Urban 3km/h
TX	Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Uplink
ULA	Uniform Linear Array
UL-SCH	Uplink Shared Channel
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telecommunications System
UNI	User-Network Interface
UPE	User Plane Entity
UpPTS	Uplink Pilot Timeslot
URI	Uniform Resource Identity (SIP)
URL	Uniform Resource Locator
USAT	UICC Application Toolkit
USB	Universal Serial Bus
USIM	Universal Subscriber Identity Module
USSD	Unstructured Supplementary Service Data

USSDC	USSD Centre
USSI	USSD simulation service in IMS
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra Wide Band
VHF	Very High Frequency
VLAN	Virtual Local Area Network
VoIP	Voice over IP
VoLGA	Voice over LTE via Generic Access
VoLTE	Voice over LTE
vPCRF	Visited PCRF
VPLMN	Visited PLMN
VPLS	Virtual Private LAN Service transport
VPN	Virtual Private Network
vSRVCC	Video SRVCC
WB	Wideband
WB-AMR	Wideband Adaptive Multi Rate
WCDMA	Wideband CDMA
WI	Work Item
WiMAX	Worldwide Interoperability for Microwave Access
WiMAX 2	IEEE 802.16m-based evolved WiMAX
WLAN	Wireless Local Area Network
WRC	World Radiocommunication Conference
XCAP	XML Configuration Access Protocol
XDM	XML Document Management
XDMS	XML Document Management Server
XML	Extensible Markup Language
ZMCSCG	Zero-Mean Circularly Symmetric Complex Gaussian

1

Introduction

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1.1 Overview

This chapter gives an introduction to the LTE-Advanced (LTE-A). The reasons behind the development and the effects of mobile broadband communications are discussed. Also the general characteristics of the LTE-Advanced technology, including comparison with the previous 3GPP releases, are described and the enhanced performance, functionalities and elements are presented at an advanced level. Finally, a guide to the book contents is given to aid navigation between the chapters.

1.2 The Structure of the Book

1.2.1 Focus of the Book

This book presents practical guidelines for the deployment of the LTE-Advanced system, including planning, dimensioning, roll-out and maintenance of networks. The focus is on functioning, construction, measurements and optimization of the radio and core networks of Release 10 and beyond 3GPP LTE and SAE standards. The book is thus an updated continuation of the previous book, *The LTE/SAE Deployment Handbook*, published by Wiley in 2011, but this text now concentrates on the advanced phase of the LTE.

This book emphasizes the practical aspects related to the developed stage of the LTE/SAE, clarifying LTE-Advanced functionality and providing advice for planning and other tasks related to system deployment. As the LTE-A is a development path for the previous 3GPP releases, also the description of the solutions and performance aspects of the prior phases are discussed, as they form the basis for the LTE-Advanced functionality.

This book discusses the development history, tracing it from the previous generations prior to Release 8, and continues from the basic Release 8 and Release 9 of LTE, including new network architecture and business models, followed by the description of technical functioning of the system with signaling, coding, modes for contents delivery, and the security aspects of

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The LTE-Advanced Deployment Handbook: The Planning Guidelines for the Fourth Generation Networks,
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core and radio system. Also, nominal and in-depth planning of the core and radio networks are discussed with field test measurement guidelines, hands-on network planning advice, and suggestions for the parameter adjustments. The book also gives recommendations for migration strategies and for the optimization of the previous systems to better support LTE-Advanced.

This book can be used in a modular way. It provides both overall descriptions for the readers who are not yet familiar with the subject as well as practical guidelines for telecom specialists. The introductory module is suitable for initial studies of the LTE and SAE technology based on the 3GPP Release 10, Release 11 and beyond. The latter part of the book is designed for experienced professionals who need practical descriptions of the physical core and radio network planning, end-to-end performance measurements, physical network construction and optimization of the system. The LTE/SAE Release 8 and Release 9 are described relatively briefly as the basic data can be found in the previously published *The LTE/SAE Deployment Handbook* (2011) from Wiley. Nevertheless, as the LTE-A is based on the foundations of LTE Release 8 and 9, the respective aspects are explained.

1.2.2 Module Structure

The module structure of this book is the following:

- Introduction (Chapters 1–2): General items and overall description of LTE-A.
- Detailed description (Chapters 3–7): Technical LTE-Advanced functionality.
- Deployment guidelines (Chapters 8–12): LTE-Advanced planning, optimization and measurements guidelines, LTE-Advanced deployment recommendations.

Figure 1.1 summarizes the contents of this book to aid navigation between the modules.

1.3 Mobile Telecommunications Development

1.3.1 LTE

The design of the LTE commenced in 2004 [1]. The driving force was the need to reduce the complexity of the terminals, lower the power consumption, decrease the equipment and utilization cost per bit, provide flexibility in the use of the established and future RF bands, and to facilitate the introduction of lower-cost services with a better user experience. Later, more detailed requirements were added, such as the reduction of the packet delivery latency and three to four times and two to three times improvement of the spectral efficiency compared to the Release 6 HSPA for downlink and uplink, respectively. Flexibility has also been an important criterion in the development of LTE to assure the suitability of the network deployment in various cases of coexisting previous networks such as GSM (*n* times 200 kHz carriers), CDMA (1.25 MHz carrier) and UMTS/HSPA (5 MHz carrier). Thus, bandwidth values of 1.4, 3, 5, 10, 15 and 20 MHz were specified in the LTE for both downlink and uplink [2]. These bandwidth values are applicable to both the FDD (Frequency Division Duplex) and TDD (Time Division Duplex) modes of LTE [3].

LTE was designed to support MIMO (Multiple Input Multiple Output) antennas as of Release 8, so that later phases increase the MIMO antennas. The design of the advanced antenna solutions for LTE devices is thus easier than, for example, for HSPA due to the integrated approach of LTE.

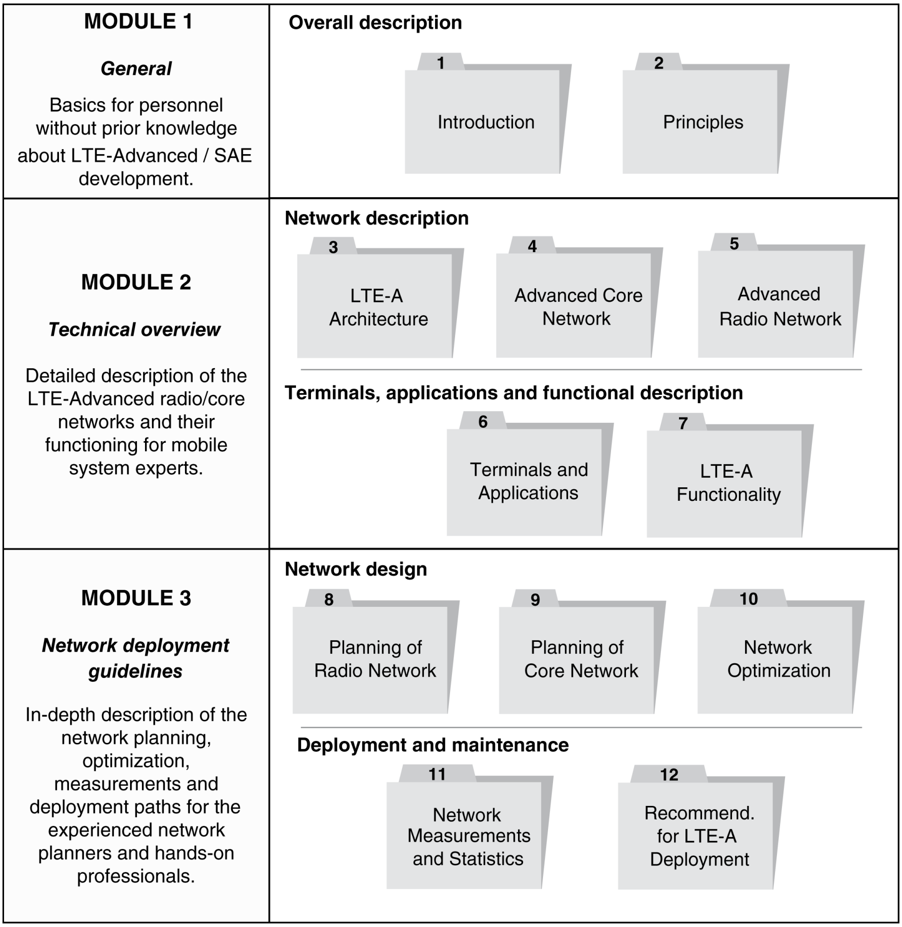
MODULE 1
General
Basics for personnel without prior knowledge about LTE-Advanced / SAE development.
Overall description
1 Introduction
2 Principles
MODULE 2
Technical overview
Detailed description of the LTE-Advanced radio/core networks and their functioning for mobile system experts.
Network description
3 LTE-A Architecture
4 Advanced Core Network
5 Advanced Radio Network
Terminals, applications and functional description
6 Terminals and Applications
7 LTE-A Functionality
MODULE 3
Network deployment guidelines
In-depth description of the network planning, optimization, measurements and deployment paths for the experienced network planners and hands-on professionals.
Network design
8 Planning of Radio Network
9 Planning of Core Network
10 Network Optimization
Deployment and maintenance
11 Network Measurements and Statistics
12 Recommend. for LTE-A Deployment

Figure 1.1 The contents of the *LTE-A Deployment Handbook*.

LTE has been designed to support especially low mobility environments up to 15 km/h with the highest defined performance values. The LTE also has categories for high performance with a terminal speed of 15–120 km/h, and for a functional performance with a speed of 120–350 km/h. 3GPP is also considering including support of a terminal speed up to 500 km/h. For the end user, the increased data rate is one of the clearest benefits of the LTE system. Figure 1.2 shows typical practical examples of the achievable LTE/LTE-A data rates with the given parameter values and releases [4]. The values depend on many parameters, such as the UE terminal category (Cat), MIMO configurations and modulation, and finally the radio conditions.

The LTE system is thus 3GPP's answer to the rapidly growing demands for increased data rates and lower latency as the multimedia contents are becoming increasingly demanding. LTE tackles these challenges, thus giving end users the benefit of a more fluent user experience of modern data communications. Also the operators now have a better means to optimize the cellular networks.

	Rel. 8	Rel. 9	Rel. 10
Peak data rate	150 Mb/s, 20 MHz, 2x2 MIMO	150 Mb/s, 20 MHz, 2x2 MIMO	1 Gb/s, 40 MHz, 8x8 MIMO
Average data rate	35 Mb/s, 20 MHz, 2x2 MIMO	35 Mb/s, 20 MHz, 2x2 MIMO	140 Mb/s, 40 MHz, 4x4 MIMO
Specification ready	03/2009	03/2010	06/2011
First networks	End of 2010	During 2012	During 2013

Figure 1.2 The timing for the LTE specifications and practical network deployments. Rel. 8 can be generalized as "Basic LTE" while Rel. 10 represents the first phase of "LTE-Advanced." In between, the "intermediate" Rel. 9 includes, for example, VoIP, femto handover and many other enhancements that pave the way for deploying the actual LTE-A.

As can be seen in Figure 1.2, the first-phase LTE is defined in Rel. 8. It provided the initial launch of the LTE networks with the basic set of functionalities on both the network and the user equipment side. Rel. 9 contains a set of enhancements, yet it still represents the pre-4G system, as the ITU-R requirements for 4G are considered. The LTE-Advanced is defined for the first time in Release 10 which contains items such as Carrier Aggregation (CA), CoMP, LIPA (Local IP Access), SIPTO (Selected Internet IP Traffic Offload), M2M, and, in general, offers an improved performance that would be sufficient to comply with the 4G requirements of ITU-R [5–7]. Nevertheless, Release 10 is still a "light" version of the fully equipped LTE-Advanced, and defines, for example, CA for two carriers which provides 40 MHz bandwidth, while the possibility of deploying CA for up to five carriers and 100 MHz bandwidth is introduced later.

The LTE-A Release 11 contains further improvements for the CA, and other relevant items, such as IMS, roaming and P2P (Peer-to-Peer). LTE-A Release 12 contains further functional additions, for example, for Wi-Fi, small cell improvements, optimization for signaling, Self-Optimizing Network features (SON), Minimization of Drive Tests (MDT), advanced receiver and MIMO improvements [8–10].

As a comparison, the peak spectral efficiency requirement for Release 8 LTE is 15 b/s/Hz and 6.75 b/s/Hz for downlink and uplink, respectively, for both FDD and TDD modes, while these values are 30 and 15 b/s/Hz for Release 10 LTE [11]. Figure 1.3 summarizes the main MIMO data rates.

LTE has clearly changed the previous concepts of telecommunications. One of the best proofs of the high importance and impact of LTE is that it no longer defines circuit-switched (CS) data transfer at all. This means that the packet-switched, "All-IP" era has reached its breaking point, and the "old-fashioned" ways of both voice and data communications via fixed line reservation are about to finish. Eventually, all telecommunications contents will be delivered via data packets, whether it is on voice calls, messaging, audio or video.

LTE refers to the developed radio interface of 3GPP systems. As the radio network now is offering considerably higher data rates with low latency, it does have a considerable impact on the rest of the network. Thus, the core network of 3GPP systems is refreshed to support adequate end-to-end performance, via new SAE (System Architecture Evolution). Figure 1.4 clarifies the terminology.

LTE coverage was not too wide when the deployment first started, even though the network construction projects may be fast in practice due to the co-location of the equipment on the

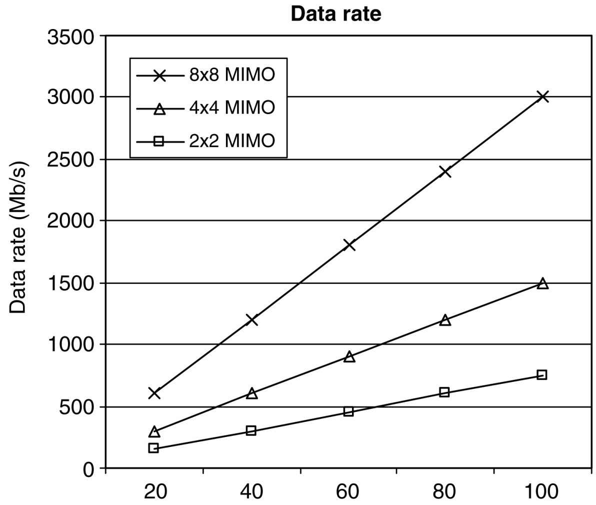

Figure 1.3 Comparison of the data rates that can be achieved with different MIMO configurations. LTE Rel. 8 still uses a maximum of 20 MHz bandwidth (1 complete carrier) while LTE-A Rel. 10 provides 40 MHz (two carriers). The full five-carrier configuration is possible with LTE-A Rel. 12.

existing sites. The large-scale LTE deployments began in 2011 and in some cases the population coverage of LTE had reached the level of the previous systems by 2014, as is the case with AT&T and Verizon Wireless in the USA.

Nevertheless, it is inevitable that the LTE coverage will consist of fragmented hot-spot areas while the basic coverage is still handled by the earlier 2G and 3G systems, for example, via GSM, UMTS, CDMA 1x and CDMA2000. As the LTE completely lacks integrated CS functionality, the respective voice calls need to be handled, when the LTE coverage ends during an established communications, as fluently as possible. For a sufficiently high-quality user-experience in these situations, the CS call is handed over to 2G/3G networks without a

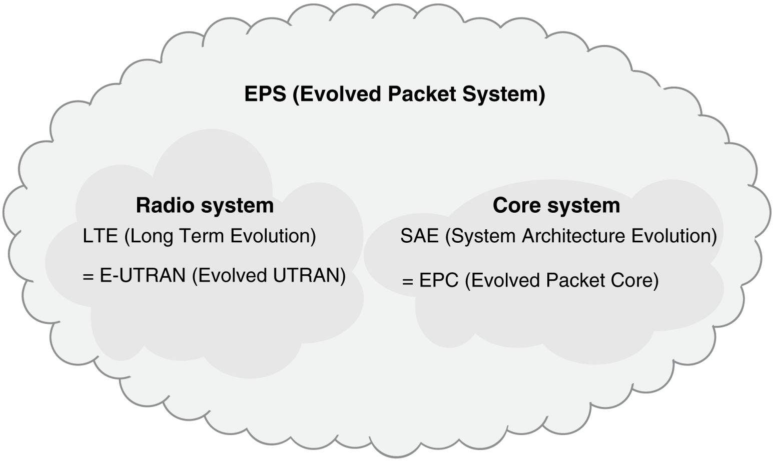
EPS (Evolved Packet System)
Radio system
LTE (Long Term Evolution)
= E-UTRAN (Evolved UTRAN)
Core system
SAE (System Architecture Evolution)
= EPC (Evolved Packet Core)

Figure 1.4 EPS consists of LTE (E-UTRAN) and SAE (EPC).

Table 1.1 The number of LTE radio resource blocks (RB) per bandwidth.

	LTE Bandwidth (MHz)					
	1.4	3.6	5.0	10	15	20
RBs	6	15	25	50	75	100

service breakdown. Some intermediate solutions have been developed for this, for example, SRVCC (Single Radio Voice Call Continuity) and CSFB (Circuit Switched Fall-Back). The final goal when serving voice call users is the fully developed and integrated IMS (IP Multimedia Sub-system) of fully deployed LTE/SAE networks. By that time, there may already be LTE-only devices available on the market. The underlying previous networks can thus be ramped down gradually, or maintained as an alternative method for those users who still have devices that require the support of the previous systems.

LTE/SAE offers many novel solutions compared to the earlier systems. One of the benefits of the system is the scalability – the bandwidth of LTE can be varied between 1.4 and 20 MHz, whereas the UMTS is tightly limited to the fixed 5 MHz band (though the UMTS can be optimized slightly by lowering the band of the NodeB elements). The larger scalability of LTE gives it the possibility of using LTE/SAE networks according to various scenarios: from stand-alone network and initial add-on network via gradual frequency re-farming, up to full-scale network and lowering the offered capacity of other networks gradually [12].

3GPP has identified a large set of frequency bands for LTE, providing the possibility of using LTE either partially or using the full 20 MHz bandwidth, depending on the band and the operator's license. The offered LTE capacity depends on the radio resource blocks (RB). The number of RBs depends on the bandwidth according to Table 1.1.

The other essential parameters of the LTE are the following, valid both for FDD and TDD bands of UMTS:

- The multiple access method in the downlink is OFDMA (Orthogonal Frequency Division Multiple Access) and SC-FDMA (Single Carrier Frequency Division Multiple Access) in the uplink.
- In the downlink, LTE can use a wide choice of MIMO configurations in order to benefit from the transmit diversity, spatial multiplexing and cyclic delay diversity.
- In the uplink, there is the possibility of using Multi-user collaborative MIMO.

In 2013, the data rate class of 100 Mb/s was typical, via class 3 UE class. The practical peak rate of LTE was up to 150 Mb/s, still in 2014, which can be obtained by using the realistic UE category 4 with 2 × 2 MIMO in the full 20 MHz bandwidth. Theoretically, a data rate of 300 Mb/s can be achieved with the UE category 5 and 4 × 4 MIMO in 20 MHz band. In the uplink, the maximum data rate of 75 Mb/s can be achieved in the 20 MHz band.

1.3.2 LTE-Advanced

1.3.2.1 Positioning in Mobile Generations

One might wonder why another mobile communications system is needed. The fact is that, based on the current data utilization statistics, there is a need for more efficient capacity offering as the numbers of mobile applications and users are increasing exponentially [13]. Thus, as was the case with previous mobile systems, LTE/SAE also has its evolution path. After the actual LTE definitions which are referred to as 3GPP LTE Release 8 and Release 9, then Release 10 and beyond define the LTE-Advanced system via a set of additional features and functionalities, such as wider bandwidth and higher degree MIMO antennas which provide increased data rates, due to the wider frequency bandwidth and other enhancements. Furthermore, the evolution path of the LTE-Advanced complies with the fourth generation IMT-Advanced requirements defined by ITU-R. As Figure 1.2 indicates, already the initial LTE-Advanced Release 10 would be capable of providing the 1 Gb/s DL data rate required by the ITU-R definitions for the 4G systems.

Even if the ITU has defined the fourth generation requirements, there has been wide debate about the terminology related to the mobile system generations. A practical definition is still to be established. The most liberal interpretations would accept the evolved UMTS HSPA data as part of the fourth generation whereas the strictest interpretation is presented by the ITU. Following the ITU principles, according to [14], the third generation requirements are listed in IMT-2000. The IMT-2000 technologies are defined in the ITU-R recommendation M.1457 which includes, for example, LTE, while the fourth generation requirements are included in IMT-Advanced.

The basic version of LTE that is defined in the Release 8 series of the 3GPP specifications can be considered a “beyond 3G, pre-4G” system, sometimes referred to as 3.9 G technology in non-standard communications. In practice, the operators are already interpreting LTE as belonging to 4G. There are thus a few interpretations of complying with 4G while the official ITU definitions dictate that the initial version of LTE does not meet the IMT-Advanced and thus 4G requirements. As an example, LTE prior to Release 10 is not able to provide the 1 Gb/s data rates as required by IMT-Advanced. Nevertheless, it is common to see the LTE, and HSPA networks being called 4G commercially. We can thus call these solutions “Industry-4G” systems. Interestingly, as the adoption of “4G” was undertaken in the commercial pre-LTE-A Release 10 era, some markets are already calling the actual LTE-Advanced Release 10 the “5G” system, while the general consensus seems to be that the ITU-compliant 5G is being brainstormed for potential deployment around the 2020 time frame. There is thus the potential for somewhat confusing terminology in practice.

Concentrating on ITU terminology, at the time the 4G candidate set was under consideration by ITU-R, 3GPP defined the compatible radio interface technology requirements. This work culminated in the 3GPP Release 9 definitions, with a set of requirements for the 3GPP LTE-Advanced system. The requirements are found in the 3GPP Technical Report 36.913 [15], which lists the functionalities that makes LTE compliant with the requirements of the ITU.

A fully compliant 4G can thus be provided via the further development of LTE, which is called LTE-Advanced. It was defined for the first time in Release 10 of the 3GPP specifications. In addition to the acceptance of LTE-Advanced for the set of 4G systems, ITU also has approved IEEE 802.16m, which is commonly known as “WiMAX 2,” as one of the 4G technologies in the IMT-Advanced family. In order to distinguish the “Industry-4G” systems that do not comply with the ITU’s 4G requirements, we can call the ITU’s version “ITU-compliant 4G.” Figure 1.5 summarizes the actual situation of the 4G technologies.

1.3.2.2 ITU Requirements for 4G Systems

ITU has been pushing for the third generation mobile communications radio technology as part of the IMT-2000 project (International Mobile Telecommunications). Some of the main

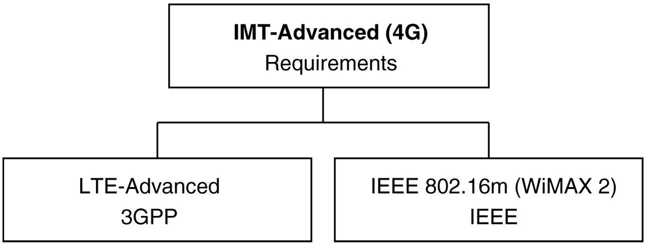

Figure 1.5 The 4G systems approved by ITU-R.

requirements for the third generation systems were already defined in 1997, with the criteria based on the peak user data rate:

- 2,048 kb/s, indoor office;
- 384 kb/s, outdoor to indoor and pedestrian environments;
- 144 kb/s, vehicular environment;
- 9.6 kb/s, satellite communications.

It should be noted that the spectral efficiency was not considered in the ITU's original 3G requirements.

ITU-R produced a more comprehensive requirement criteria list for the 4G mobile communications radio systems, that is, IMT-Advanced. Some of the main requirements are [16]:

- enhanced peak data rates: 1 Gb/s in DL for low mobility scenarios and 100 Mb/s for high mobility scenarios in the downlink direction;
- a high degree of common worldwide functionality while flexibility in supporting a wide range of local services and applications in a cost-efficient way;
- service compatibility of IMT and fixed networks;
- compatibility capability with other radio systems;
- high-quality mobile services;
- user equipment that is useful in a global environment;
- provision of user-friendly applications, services and equipment;
- global roaming.

1.3.2.3 3GPP Requirements for 4G

The LTE-Advanced requirements are listed in the 3GPP specification number 36.913 (Requirements for Further Advancements for E-UTRA – LTE-Advanced) [17]. The LTE-Advanced was defined for the first time in the Release 10 series of 3GPP specifications, which was frozen in March 2011.

The key requirements of ITU-R with the further additions of 3GPP for the fourth generation systems are the following:

- 1 Gb/s peak data rates in the downlink;
- 500 Mb/s peak data rate in the uplink;
- three times higher spectrum efficiency than in the LTE system;

- 30 b/s/Hz peak spectrum efficiency in the downlink;
- 15 b/s/Hz peak spectrum efficiency in the uplink;
- support of scalable bandwidth and spectrum aggregation where a non-contiguous spectrum needs to be used;
- latency requirement for the transition from idle to connected mode faster than 50 ms, and after that, less than 5 ms (one-way) for an individual packet transmission;
- two times higher user data throughput in the cell edge than in LTE;
- three times higher average user data throughput than in LTE;
- same mobility performance as in LTE;
- LTE-Advanced must be able to be compatible with LTE and the previous 3GPP systems.

3GPP has defined the 4G candidate interface solutions in Release 9 as a study item [17]. The 3GPP requirements are based on the IMT-Advanced requirements as well as the operator feedback, and they thus comply with the ITU-Advanced or present even stricter requirements. Furthermore, one important aspect of 3GPP has been to guarantee backwards compatibility with the previous 3GPP releases for LTE. This means that the LTE user equipment should function in LTE-Advanced networks, and LTE-Advanced user equipment must work in previous releases of LTE networks.

The LTE spectrum is much more variable than has been the case for the previous systems. The initial frequency plan has already been drawn up by the WRC-07 (World Radiocommunication Conference of ITU-R) in line with the overall IMT-Advanced. Nevertheless, ITU has renamed what previously was called the "IMT-2000 spectrum" (that was dedicated to the third generation systems) as a generalized format "IMT spectrum." The motivation was to include the previous 3G (IMT-2000) bands also as such for 4G (IMT-Advanced). This also means that the 3G spectrum and the 4G spectrum are not differentiated. Instead, there is a common "pool" of IMT frequencies. This gives the necessary flexibility for local deployment. The drawback of this approach is that there are and will be even more fragmented bands, which cause problems, especially for the user equipment manufacturers. The essential question for the OEMs (Original Equipment Manufacturer) is thus, what set of LTE (and GSM/UMTS) frequency bands from dozens of options is good enough per market area, taking into account also the need for roaming? This is quite a different challenge compared to the previous 3GPP band selection, with quad-band GSM and penta-band UMTS giving the maximum coverage with standard chip support.

The system performance of the LTE-Advance complies with the statements presented in the IMT-Advanced requirement set, or exceeds them. As an example, the DL peak data rate requirement of 1 Gb/s is achieved with LTE-Advanced when 4 × 4 MIMO antennas are deployed with more than 70 MHz bandwidth [18]. In practice, the LTE compliance with the IMT-Advanced requirements is fulfilled gradually. As an example, Release 8 LTE does not comply with the ITU definitions of 4G spectral efficiency in the uplink.

Table 1.2 summarizes the targets of the spectral efficiency for the LTE Rel. 8/9, LTE-Advanced Release 10 and IMT-Advanced. It is worth noting that the LTE-A targets are designed to be more demanding than the IMT-Advanced values, especially for the peak performance.

LTE-Advanced also introduces new user equipment categories (Cat). The LTE Release 8/9 defined Cat 1-5, and LTE-A defines further Cat 6-8. Table 1.3 clarifies the performance of each category. Releases 12 and 13 define further LTE-M with Category 0 (Cat 0 capability for machine type communications (MTC) with a peak rate of 1 Mb/s.

Table 1.2 Comparison of LTE, LTE-A and IMT-Advanced performance targets in terms of Spectral Efficiency (SE).

Target item	LTE Rel. 8/9 [14]	LTE-A Rel. 10(+) [8]	IMT-Advanced [7]
Peak SE, DL	16.3 (4 × 4 MIMO)	30 (8 × 8 MIMO)	15 (4 × 4 MIMO)
Peak SE, UL	4.32 (64-QAM SISO)	15 (4 × 4 MIMO)	6.75 (2 × 4 MIMO)
Cell SE, DL, 3 km/h, ISD 500 m, 2 × 2 MIMO	1.69	2.4	—
Cell SE, DL, 3 km/h, ISD 500 m, 4 × 2 MIMO	1.87	2.6	2.6
Cell SE, DL, 3 km/h, ISD 500 m, 4 × 4 MIMO	2.67	3.7	—
Cell-edge user SE, DL, 5%-ile, 10 users, Inter Site Distance 500 m, 2 × 2 MIMO	0.05	0.07	—
Cell-edge user SE, DL, 5%-ile, 10 users, Inter Site Distance 500 m, 4 × 2 MIMO	0.06	0.09	0.075
Cell-edge user SE, DL, 5%-ile, 10 users, Inter Site Distance 500 m, 4 × 4 MIMO	0.08	0.12	—

Note: Values are presented in bits/s/Hz.

1.3.2.4 Documentation

The feasibility study of 3GPP for LTE-A is presented in the 3GPP Technical Report (TR) 36.912 [6]. The feasibility study concluded that the LTE-A requirements and performance should at a minimum comply with the IMT-Advanced requirements for 4G. In addition, it was noted that LTE Rel. 8 would meet most of the 4G requirements, excluding the uplink spectral efficiency and peak data rates. The lack of this support is solved by including a set of LTE-Advanced features, such as:

- carrier Aggregation of up to five carriers which provides a wider bandwidth;
- enhancements for uplink multiple access;
- advanced MIMO techniques for multiple antenna transmission.

Table 1.3 The LTE/LTE-A UE categories.

Category	DL data rate, max (Mb/s)	UL, data rate, max (Mb/s)
1	10	5
2	50	25
3	100	50
4	150	50
5	300	75
6	300	50
7	300	150
8	1200	600

These items already assure as such the compliance of the IMT-Advanced requirements with LTE-A. Nevertheless, a set of future items has also been identified for additional enhancements:

- Coordinated Multipoint Transmission and Reception (CoMP);
- relaying;
- Heterogeneous Networks (HetNet).
- enhancements for Self-Optimizing Network (SON);
- enhancements for the mobility of HeNB (Home eNB);
- RF requirements for the fixed wireless Customer Premises Equipment (CPE).

The proposal for the further functionalities and performance enhancements are presented in *Further Advancements for E-UTRA Physical Layer Aspects* [19]. Further details on the proposals can also be found in [10,20]. The background to the LTE-A requirements development can be found in [6,15,21,22–24] and other useful information in [7,11,13,25–32,33].

1.4 Motivation for LTE-Advanced Deployment

Traditionally, during the 2G era and in the beginning of the 3G system deployment, data service use was at a notably low level, typically representing a maximum of 2% of the whole traffic. The circuit-switched voice service and short message service were the dominant teleservices. Even the introduction of the first packet data solutions, that is, GPRS (General Packet Radio Service) and its developed version, EGPRS (Enhanced GPRS) or EDGE (Enhanced Data Rates for Global Evolution) did not increase the level of data service use considerably though they were necessary steps in the mobile networks for the provision of cost-optimized method for the bursty traffic of the Internet Protocol. Nowadays, the circuit-switched data is considered old-fashioned and expensive for both users and operators, and it is thus disappearing from the operators' service sets.

Only recently the level of use of packet data has increased as a result of considerably higher data rates and lower latency, which makes the mobile data communications comparable or in some cases even more attractive than a typical Internet subscription. As a result, more applications have been developed for both leisure time purposes as well as for business use. One of the main drivers for future data use is the growth of smart phone penetration [25]. As an example, Informa has estimated that in 2010, 65% of global mobile data traffic was generated by the proportion of 13% of mobile subscribers who use smart phones, with the average traffic per user of 85 MB per month. Japan is the most active country for mobile data usage, with 199 MB per month.

The LTE and LTE-Advanced will provide the very necessary capacity and data rates for end users in the forthcoming years. LTE/LTE-A use is at a very active stage of development at the moment. According to the GSM Association (GSMA) [34], LTE is the fastest developing mobile system technology ever. GSMA forecasted 284 commercial LTE networks in 87 countries by the end of 2013. As an example, the ITU statistics also show that there were only 14 LTE commercial networks in Latin America by the end of April 2013 [35]. It is thus one of the fastest growing areas in the global LTE markets.

GSMA has further reported that by the year 2017, the one billion milestone for the number of the LTE users will be reached [36]. By the end of 2013, there were 176 million LTE connections. According to the GSMA forecast, also the number of the LTE networks will increase from about 250 that were deployed in 2013 to about 500 by 2017.

Not only the need for the actual user data transfer is increasing, but also the related signaling load will be heavier over time. The combined user data and signaling load must thus be

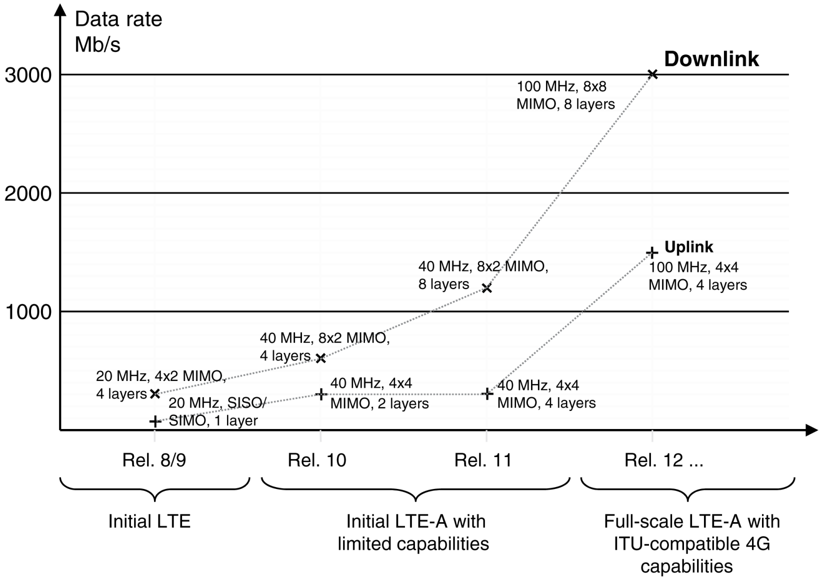

Figure 1.6 The data rate evolution scenarios of LTE/LTE-A.

guaranteed for the provision of sufficiently smooth user experiences, which is a result of the high data rate and throughput, and low latency. These are especially important in delay-critical applications like real-time gaming and video conferencing.

LTE/LTE-A addresses these current and future challenges. Figure 1.6 summarizes the LTE data rate evolution towards the fully equipped LTE-Advanced.

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2

LTE-Advanced Principles

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2.1 Introduction

The LTE refers to the long-term evolution of the 3GPP radio network. It is a synonym for the evolved UTRAN, that is, E-UTRAN (UMTS Terrestrial Radio Access Network), which defines the new LTE radio interface as of Release 8 of 3GPP. Release 9 provided a further enhancement for LTE until Release 10 formed the basis for the ITU 4G-compatible system [1–3]. This chapter describes the main principles of the LTE-Advanced technology, the standards and functionalities that make the LTE-Advanced as defined in 3GPP Release 10 and beyond, compared to the previous releases.

The LTE, as of Release 8, enhances the performance of the IP domain of the networks, and gives more flexibility to the design of the radio network via variable bandwidth per carrier and carrier aggregation. The LTE provides several channel bandwidths, which is useful in the general network evolution, including the re-farming strategies [4–13]. LTE can use either FDD (Frequency Division Duplex) or TDD (Time Division Duplex) modes. LTE is based on the OFDMA (Orthogonal Frequency Division Multiple Access) technology in downlink, and the SD-TDMA in uplink, which optimizes the radio interface for the mobile environment especially in the presence of multipath radio components and fast fading of multiple signals. LTE can also use the latest technologies on top of the basic solution, including 64-QAM (64-state Quadrature Amplitude Modulation) and different configurations of the MIMO (Multiple Input Multiple Output) antennas.

The rationale for the LTE has thus been to assure the continuity of competitiveness of the 3G system for the future in such a way that user demand for higher data rates and quality of service is fulfilled. Due to the modern development in general, LTE was designed as a packet-switched system in an optimal way. Other advantages of 3GPP are continued demand for CAPEX and OPEX reduction, low complexity and the avoidance of unnecessary fragmentation of technologies for paired and unpaired band operation [2].

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The developed UTRAN, that is, the LTE radio system, contains only a single element which is the LTE base station, eNodeB (eNB) [14]. This refers to the evolved NodeB of the 3GPP networks. There is thus no longer a separate controller element in LTE compared to the previous UMTS/HSPA releases. Instead, the control functionality has been concentrated in the eNodeB.

$$\text{“}LTE\text{”} = \text{“}E\text{-}UTRAN\text{”} = 3GPP\,Rel.8/9$$

The rest of the 3GPP network which is not related to the radio is SAE, which refers to the System Architecture Evolution of the 3GPP core network. Thorough feasibility studies have been carried out as a basis for the selection of the technology as indicated in [15]. Also the feasible protocols and physical layer evolution have been investigated thoroughly, as indicated in [16,17].

The official 3GPP term for the evolved core part is EPC (Evolved Packet Core). As the name indicates, the system is based on IP traffic, and LTE thus does not have any integrated connections defined for the circuit-switched domain.

$$\text{“}SAE\text{”} = \text{“}EPC\text{”}$$

The complete solution of the evolution is called EPS, that is, Evolved Packet System, which includes both LTE and EPC. Like for the term LTE, SAE is no longer officially recognized in the standardization terminology. Nevertheless, it was introduced to the market with such enthusiasm that it has been retained in the spoken terminology. For this reason, either SAE or EPC can be used to describe the evolved core, although the standard term EPC is recommended for uniformity.

$$\text{“}EPS\text{”} = \text{“}LTE\text{”} + \text{“}SAE\text{”} = \text{“}E\text{-}UTRAN\text{”} + \text{“}EPC\text{”}$$

Thus, the basic LTE refers to the 3GPP Releases 8 and 9, while LTE-Advanced is defined for first time in 3GPP Release 10.

$$\text{“}LTE - A\text{”} = [3GPP\,Rel.10, 3GPP\,Rel.11, \ldots]$$

The principle of the functionality of the LTE and LTE-Advanced user equipment with LTE and LTE-Advanced networks is presented in Figure 2.1. As a summary, the LTE UE (of Releases 8 and 9) is able to work with the capabilities it supports with the LTE as well as LTE-Advanced (Release 10 and beyond) eNodeB. The LTE UE thus does not benefit from the advanced capabilities of LTE-A eNodeB, but it functions in any case with the set of functionalities it is able to use according to Releases 8 and 9.

In the same fashion, the LTE-A UE can work with both LTE and LTE-A eNodeB, but it cannot achieve LTE-A performance with LTE eNodeB.

As a summary, LTE-A is backwards compatible with LTE as can be seen in Figure 2.1. It eases the network deployment scenarios and provides a means for the straightforward migration from LTE stage. LTE-A provides higher data rate and capacity mobile broadband access, extending the 20 MHz bandwidth of basic LTE up to 100 MHz and enhancing the theoretical 200 Mb/s data rate of LTE up to 1–3 Gb/s, depending on the set of the functionalities. The first demos of Gb/s range were seen in 2014 [18].

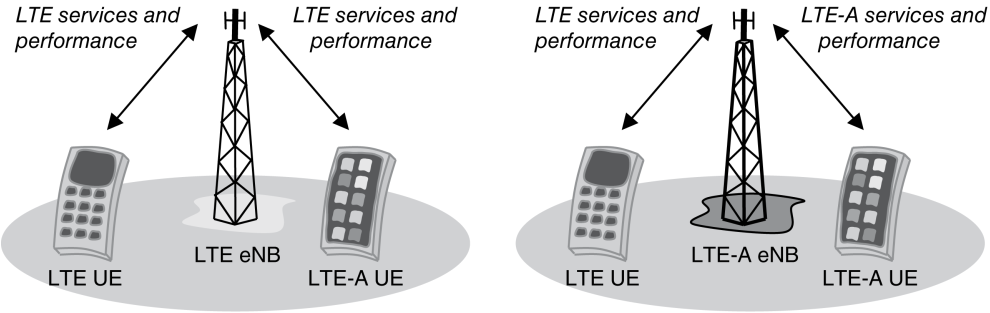
LTE services and performance
LTE services and performance
LTE UE
LTE eNB
LTE-A UE
LTE services and performance
LTE-A services and performance
LTE UE
LTE-A eNB
LTE-A UE

Figure 2.1 The backwards compatibility of LTE and LTE-Advanced. The LTE-A performance can be obtained with LTE-A eNB and LTE-A UE. Nevertheless the LTE-UE is backwards compatible with LTE eNB, and LTE UE is capable of working via LTE-A eNB with the LTE constraints.

2.2 LTE and SAE Standardization

2.2.1 Working Groups

The LTE and SAE are standardized in the 3GPP (3rd Generation Partnership Project). 3GPP works, producing 3GPP specification, on GSM, W-CDMA and LTE specifications. The GSM is a part of the second-generation mobile network solutions. GSM includes terms like GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for GSM/Global Evolution). The general term for the 2G radio network of 3GPP is GERAN (GSM/EDGE Radio Access Network). The third generation includes standardization terms to describe 3G networks like UTRAN (UMTS Terrestrial Radio Access Network), HSPA (High Speed Packet Access), European UMTS (Universal Mobile Telecommunications System) and Japanese FOMA (Freedom of Mobile Multimedia Access).

The standardization work of GSM and UMTS is a continuous process. The work was initiated in ETSI where the GSM and first UMTS standards were created. In 1999, the 3GPP took over both the GSM and UMTS and has been developing the standards ever since. The standardization work is ongoing and the outcome is a set of new releases every now and then. Revised versions of many of the specifications are produced up to four times a year. The organization is democratic, and the solutions are selected thus via voting in sub-groups and in the quarterly TSG plenary meetings of 3G. The TSG GERAN meets five times a year, however.

Figure 2.2 shows the current set-up of the standardization groups of 3GPP (status in September 2015) as interpreted from the information of reference [19]. The RAN groups have defined the LTE specifications while SA has made respective definitions for the SAE.

2.2.2 How to Find Information from Specs?

Relevant information about the LTE/SAE and previous 3GPP definitions can be found on the 3GPP web page (www.3gpp.org), and all the 3GPP specifications can be accessed via the link www.3gpp.org/specifications/79-specification-numbering. Furthermore, the LTE/LTE-A specifications can be accessed directly via www.3gpp.org/DynaReport/36-series.htm. The 3GPP standards and specifications numbering is logical, the prefix indicating the main topic, and the latter part indicating the more specific item for each Release.

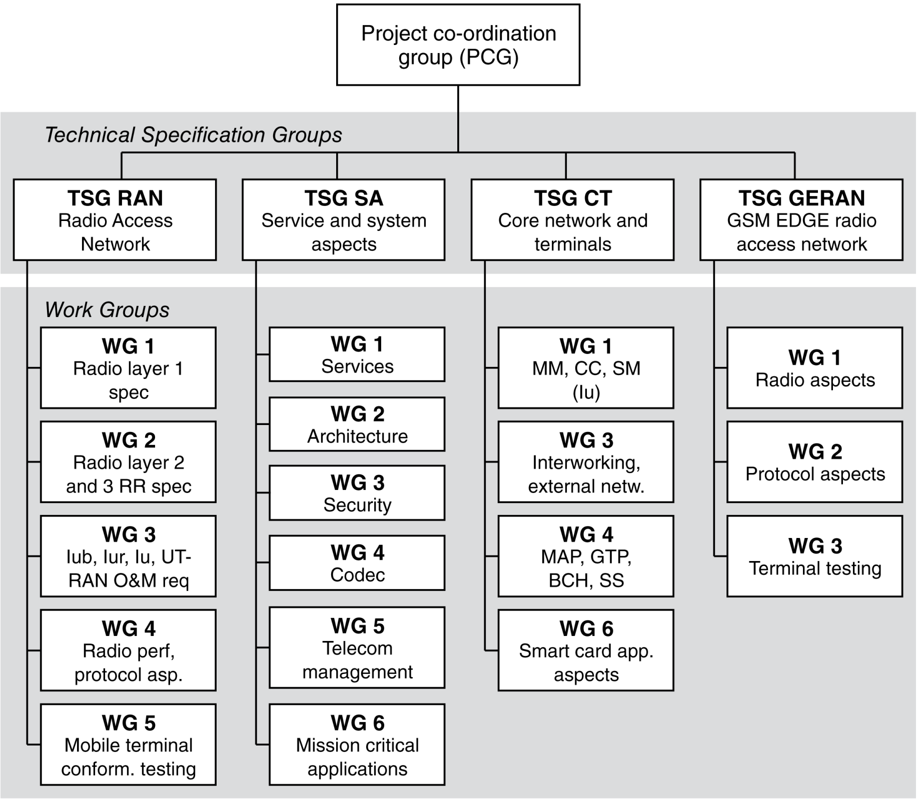
Project co-ordination group (PCG)
Technical Specification Groups
TSG RAN
Radio Access Network
TSG SA
Service and system aspects
TSG CT
Core network and terminals
TSG GERAN
GSM EDGE radio access network
Work Groups
WG 1
Radio layer 1 spec
WG 2
Radio layer 2 and 3 RR spec
WG 3
Iub, Iur, Iu, UT-RAN O&M req
WG 4
Radio perf, protocol asp.
WG 5
Mobile terminal conform. testing
WG 1
Services
WG 2
Architecture
WG 3
Security
WG 4
Codec
WG 5
Telecom management
WG 6
Mission critical applications
WG 1
MM, CC, SM (Iu)
WG 3
Interworking, external netw.
WG 4
MAP, GTP, BCH, SS
WG 6
Smart card app. aspects
WG 1
Radio aspects
WG 2
Protocol aspects
WG 3
Terminal testing

Figure 2.2 3GPP standardization is undertaken by the Technical Specification Groups (TSG). They include Radio Access Networks (RAN), System Architecture (SA), Core Networks and Terminals (CT) and GSM EDGE Radio Access Network (GERAN). The final standards are approved or rejected in plenary meetings.

The LTE (Evolved UTRA) and LTE-Advanced radio technology specifications can be found in the 3GPP 36 series.

The main topics can be investigated via the overall specification numbering scheme as presented in Table 2.1. The 3GPP specifications are divided into thematic topics that are indicated by the first number of the specification that can be technical specification (TS), or technical recommendation (TR).

The LTE/SAE specific definitions are found in 36 series, although there are many interdependencies between 36 series and other series. This is logical as LTE uses the same base as previous 3G standards have defined, the main differences being in the radio channels, access methods, and other radio-related new or modified definitions.

The specification number further consists of the sub-classification (the decimal part) and version with the respective date when the specification was formalized in the 3GPP acceptance processes. The front page of 3GPP LTE/SAE specification consists of the information as seen in the example of Figure 2.3.

Table 2.1 The 3GPP specification division. Please note that the 47-series does not currently include any documents.

Topic	Specification/recommendation numbering	
	(GSM specific original ETSI numbers in transparences), Release 4 and beyond in bold	3G and GSM, Release 99 and later
Requirements	(01) **41**	**21**
Service aspects of stage 1	(02) **42**	**22**
Technical realization of stage 2	(03) **43**	**23**
Signaling protocols of stage 3, UE-network	(04) **44**	**24**
Radio aspects	(05) **45**	**25**
Voice codecs	(06) **46**	**26**
Data	(07) **47**	**27**
Signaling protocols of stage 3, RSS – CN	(08) **48**	**28**
Signaling protocols of stage 3, intra-fixed-network	(09) **49**	**29**
Programme management	(10) **50**	**30**
Subscriber Identity Module (SIM), Universal Subscriber Identity Module (USIM), IC cards, test specifications	(11) **51**	**31**
Operations, Administration, Maintenance, and Provisioning (OAM&P) and charging	(12) **52**	**32**
Access requirements and test specifications	(13) **13**	**N/A**
Security aspects	(Included in other specs) **Included in other specs**	**33**
UE, SIM and USIM test specifications	(Included in other specs) **11**	**34**
Security algorithms	(Not public) **55**	**35**
Evolved UTRA (LTE) and LTE-Advanced radio technology	(N/A) **N/A**	**36**
Multiple radio access technology aspects	(N/A) **N/A**	**37**

Release 8 is the first one where definitions for the LTE and SAE are found. The standards are divided into the following categories at the moment:

- Release 8, the basis for LTE. Contains basic functionality for, for example, self-configuration plug and play, neighbor cell relation and auto cell ID, and Inter Cell Interference Coordination (ISIC).
- Release 9, relatively minor functional additions for LTE, and requirements for the ITU-R compliant 4G of Release 10 LTE-A. Contains, for example, load balancing and energy-saving functionality, handover and RACH optimization.
- Release 10, major performance additions, the basis for LTE-Advanced. Contains enhancements for coverage and capacity optimization.
- Release 11 and beyond, further enhancements for LTE-Advanced.

The publication of Release 8 and Release 9 offers the telecommunications industry a logical evolution towards the next generation mobile networks, which in terms of 3GPP refers to LTE.

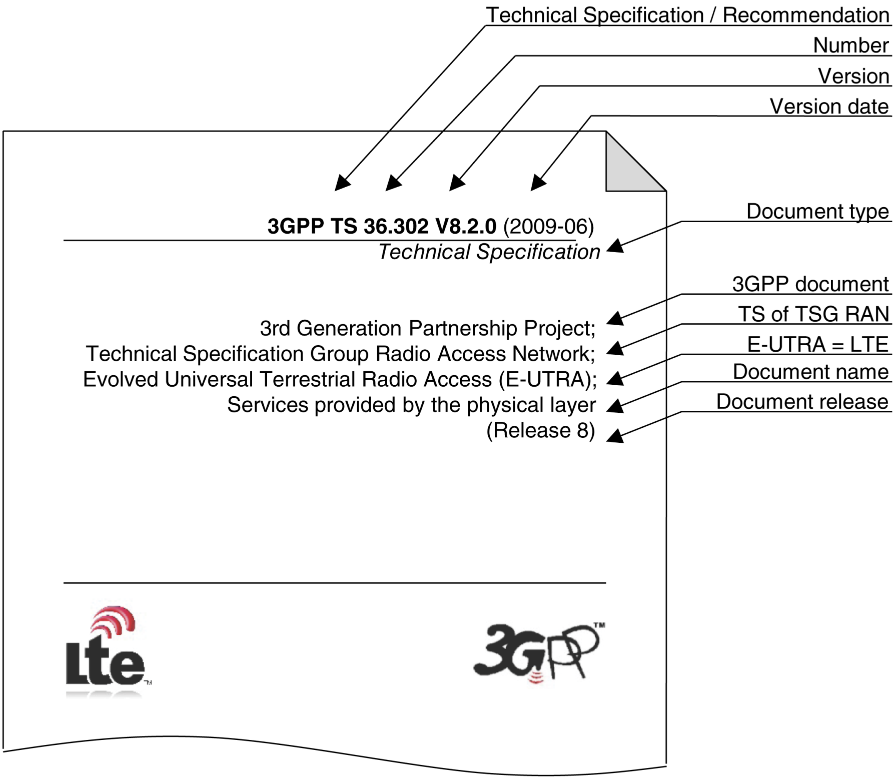
Technical Specification / Recommendation
Number
Version
Version date
3GPP TS 36.302 V8.2.0 (2009-06)
Technical Specification
Document type
3GPP document
TS of TSG RAN
E-UTRA = LTE
Document name
Document release
3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Evolved Universal Terrestrial Radio Access (E-UTRA);
Services provided by the physical layer
(Release 8)
Lte
3GPP

Figure 2.3 An example of the 3GPP standard's cover page. Version 8 and 9 refer to Release 8 and 9, respectively, that is, basic LTE, while version 10 and beyond are related to the LTE-Advanced. The LTE and 3GPP logos presented by courtesy of ETSI and 3GPP.

The common standardization makes LTE compatible with legacy networks, which is one of the important arguments for the development [20,21]. The work also continues along with the LTE and LTE-A deployments.

All the new LTE-related Release 8 and beyond definitions can be found in the 3GPP 36 series. Table 2.2 lists the main topics of the specifications.

In addition to the Technical Specifications, there is also Technical Recommendations (TR) defined in TR 36.8*xx* and TR 36.9*xx*. Please refer to the complete LTE/LTE-A TS and TR list on the 3GPP web page [22].

Table 2.2 The main division of the LTE specifications.

Technical Standard (TS)	Main topics
TS 36.1*xx*	Equipment requirements for terminals and eNodeB elements
TS 36.2*xx*	Physical layer (1) specifications
TS 36.3*xx*	Layer 2 and 3 specifications
TS 36.4*xx*	Network signaling specifications
TS 36.5*xx*	User equipment and conformance testing specifications

Each Release contains additional and advanced definitions which has an effect on the LTE/LTE-A performance and also on network planning. Furthermore, the new releases typically increase also the set of options and mandatory features, for example, for network optimization. This, in turn, has a positive effect on the LTE/LTE-A network deployment.

2.3 3GPP Evolution Path

The 3GPP systems have been evolving all the time, and there are fundamental differences between the architectural solutions between releases since the first GSM systems up to the LTE/SAE. Figure 2.4 shows the architecture principles of the 3GPP systems.

As can be seen from Figure 2.4, unlike any earlier 3GPP system, the LTE/SAE as of Release 8 is based on purely flat architecture. This means that there is only one element type for the radio network, and one element type for core network, which also is the case for the LTE-Advanced as of Release 10. It should be noted that the developed stage of LTE includes with the Home eNodeB concept different options for the connectivity to SAE as presented later in this book.

The need for the higher data rates and faster response times of signaling than GSM and UMTS/HSPA could offer was the main trigger for the initiation of LTE/SAE standardization. The reasoning behind this need is the forecast for the data evolution that indicates the increasing importance of the mobile data services. On the other hand, the cost reduction is one of the main drivers for network operators to introduce LTE/SAE.

In order to actually offer considerably enhanced user experiences, the optimization of the delay is essential. This means that the minimized latency and round-trip-delay will lead to the higher TCP traffic throughput and lower UDP/RTP traffic jitter, and eventually to higher quality real-time services. Also fast service availability is essential, which is done via low bearer set-up times. These benefits increase the awareness of LTE, and also increase the use of the networks.

As the trends clearly show, the number of mobile subscribers using Internet services (web browsing, e-mail, social networks with text and multimedia chat) is increasing exponentially. At the same time, the data transfer that was traditionally dominated by the business user community is nowadays being accessed by the younger user profiles, who have been accustomed to using the same services in fixed Internet already for several years.

In order to provide fluent user experiences, it is essential to reduce the latency of the signaling, or control plane messaging. The round-trip delay that the previous 2G and 3G networks contain is seen as a limiting factor in the provision of fluent services.

The advantage of the pure IP-based mobile network architecture is the possibility of simplifying the functionality. The already proven principles of the IP networks provide the reduction of the network elements, and thus the radio as well as the core network can be constructed by using fewer elements than previously it was possible to do. LTE/SAE and its evolution thus offer new means for techno-economic network optimization.

Thanks to the pure IP solution, EPC is optimized to deliver the data in the PS domain. In the previous solutions of 2G/3G, the data delivery has not been ideal due to the need for support of both circuit and packet-switched domains. Nevertheless, although LTE/SAE lacks an integrated CS domain, it is backwards compatible with the previous services such as circuit-switched voice call via mechanisms that support the service continuity via, for example, roaming between 2G, 3G and LTE networks. EPC and EPS also provide mechanisms for mobility when the terminals are attached in 2G, 3G and LTE networks. The basis of the

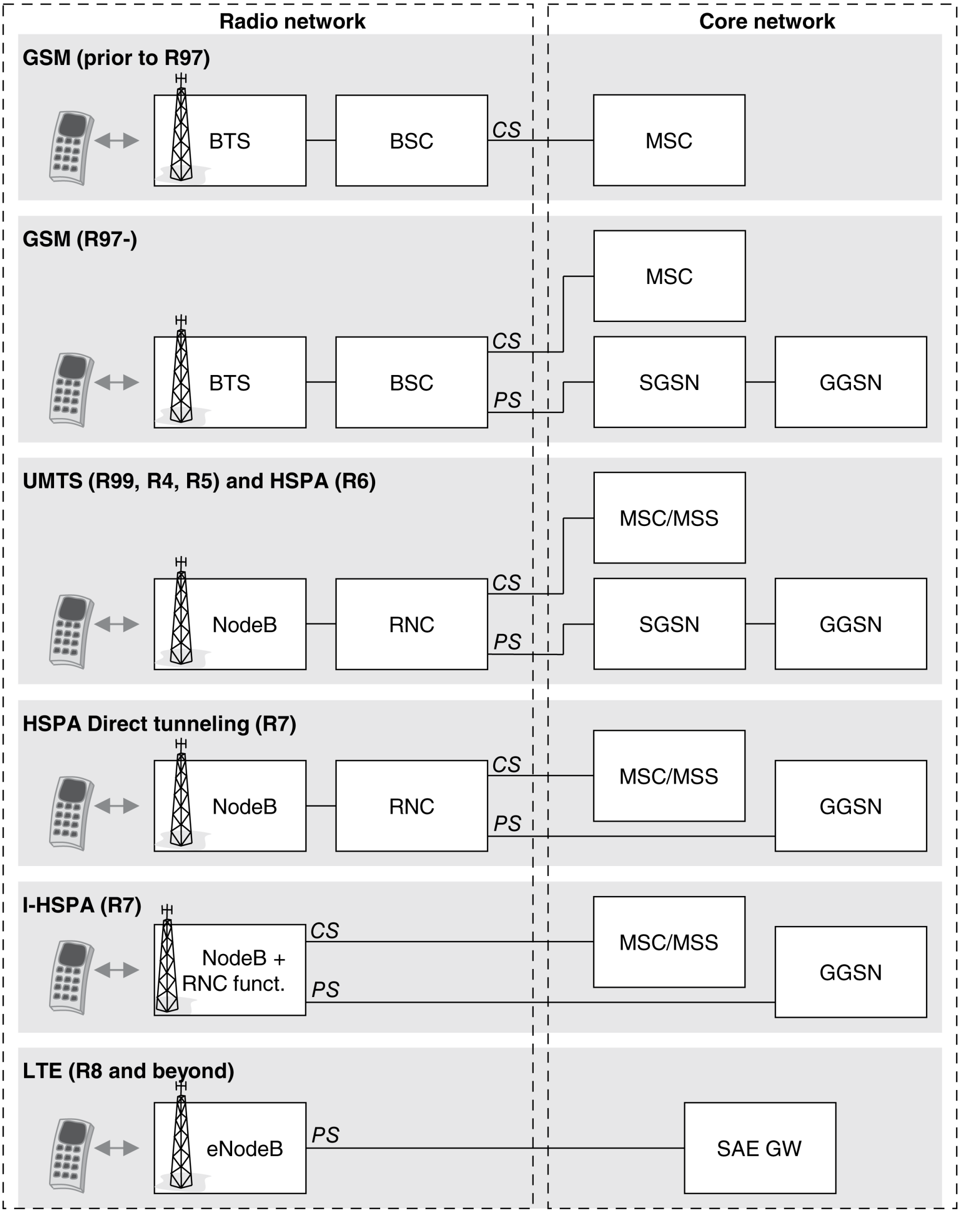
Radio network
Core network
GSM (prior to R97)
BTS
BSC
CS
MSC
GSM (R97-)
MSC
BTS
BSC
CS
PS
SGSN
GGSN
UMTS (R99, R4, R5) and HSPA (R6)
MSC/MSS
NodeB
RNC
CS
PS
SGSN
GGSN
HSPA Direct tunneling (R7)
NodeB
RNC
CS
PS
MSC/MSS
GGSN
I-HSPA (R7)
NodeB +
RNC funct.
CS
PS
MSC/MSS
GGSN
LTE (R8 and beyond)
eNodeB
PS
SAE GW

Figure 2.4 The evolution of 3GPP network architecture. LTE simplifies the layout of the network via the flat architecture by providing only packet-switched connections.

mobility is formed via GTP and PMIP mobility protocols. A new GTP version has been introduced by 3GPP (GTPv2) for the control plane signaling of the EPC. For the user plane transport, the previously defined GTPv1-U is still valid without the need for change.

For the non-3GPP access systems, for example, WLAN and WiMAX, the LTE/SAE supports mobility based on the generic mobility protocols of IETF, like PMIPv6 and

DSMIPv6 [23,24]. For the special case of CDMA2000 eHRPD system, the handover mechanism to LTE was designed by introducing special control plane and user plane interfaces into the EPC. This facilitates the transfer of the information from one access network to another, prior to the handover procedure, which optimizes and harmonizes the actual handover procedure. There also is fall-back mechanism defined from LTE/LTE-A to previous 3GPP networks [25].

As a summary, the LTE-Advanced is a continuum from the basic LTE. The LTE-Advanced is defined as of Release 10 whereas the basic LTE is formed in Releases 8 and 9. The main focus of the LTE-Advanced is to offer higher capacity in a cost-efficient way, and at the same time, to comply with the ITU requirements for the 4G mobile communications system.

As summarized, the major features of the LTE-Advanced are [26]:

- Increased peak data rate for DL 3 Gb/s and for UL 1.5 Gb/s.
- Higher spectral efficiency, from a maximum of 16b/s/Hz in Release 8 to 30 b/s/Hz in Release 10.
- Increased number of simultaneously active subscribers.
- Improved performance at cell edges. For DL 2 × 2 MIMO, the value should be at least 2.40 b/s/Hz/cell.

The major means of achieving the LTE-Advanced performance are [27]:

- Carrier Aggregation (CA).
- MIMO enhancements.
- Relays.
- CoMP.
- HetNet enhancements (eICIC, feICIC).

Other enhancements that provide further performance for LTE-Advanced in Release 10 and beyond are:

- Self-Organizing/Optimizing Network (SON) evolution.
- IMS Service Continuity (ISC).
- IMS Centralized Services (ICS).
- Home eNodeB, LIPA, SIPTO.
- Fixed Mobile Convergence (FMC).
- Machine to Machine (MTM) communications.
- SVRCC.
- Wi-Fi Inter-working.
- UICC.
- eMBMS.
- Non-Voice Emergency Services.

2.4 LTE-A Spectrum Allocation

There are various frequency band options available for the LTE system, depending on the country and continent. The LTE networks can be deployed in existing and new frequency bands. The most popular bands since the launch of the LTE networks have been:

- The 1800 MHz Band 3 that is currently widely used for the GSM system. According to [33], Band 3 is used in 43% of all the deployments.
- A new 2600 MHz Band 7 is becoming available globally in various parts and is one of the most popular for the LTE deployments. According to [28], Band 7 is used in 27% of the deployments.
- The 700 MHz band that has been typically used for the analog TV broadcast networks and that are re-farmed due to the digitalization of the TV systems. The most used 700 MHz LTE bands are 12, 13, 14, 17 [29].
- The 800 MHz Band 20 is increasingly popular for LTE deployments. According to [28], Band 20 is used in 13% of the deployments.
- The 850 MHz Band 5 and 1900 MHz Band 25 that are widely used for GSM in North America.
- The 2100 MHz band outside of the America region, and the combined 1700 MHz and 2100 MHz bands in the America region, that are widely used for the previous 3G systems, that is, UMTS/WCDMA and HSPA. This AWS band 4 is also highly popular. According to [28], AWS Band 4 represents 9% of the world's deployments.

For the TDD deployments, [28] lists the most popular bands up to February 2014. These bands are:

- Band 40 in 2.3 GHz (15 networks).
- Band 38 in 2.6 GHz (9 networks).
- Band 41 in 2.6 GHz (5 networks).
- Band 42 in 3.5 GHz (3 networks).
- Band 39 in 1.9 GHz (1 network).

The initial LTE deployment has occurred especially in the FDD bands in 1800 MHz, 2600 MHz, 700 MHz, 800 MHz and combined 2100 MHz/1700 MHz bands. Up to February 2014, there were a total of 244 FDD-LTE operators, 17 TDD-LTE operators, and 13 operators using both FDD and TDD modes. Note that China Mobile uses LTE-TDD bands 39, 40 and 41.

Nevertheless, LTE/LTE-A specifications include such a wide variety of already existing and new frequency bands that there will inevitably be a need for fragmented LTE/LTE-A device markets. In other words, instead of devices that contain all or a major part of the 3GPP frequencies, they tend to support a subset of localized markets. This means that the device frequencies of, for example, Latin America will differ partially from the North American frequencies. It is thus a very important task for the Original Equipment Manufacturers (OEM) to select the optimal set of frequencies in order to support widely enough the country-level and continent's frequencies as well as wider roaming use cases between continents. The methodology for the LTE/LTE-A user equipment RF band selection and optimization of the most feasible frequencies is discussed in a case example presented in Chapter 6 which shows the deployment aspects of the LTE/LTE-A terminals. Furthermore, Chapter 5 details the radio interface of LTE/LTE-A, including the identified RF bands that are present in Section 2.5.2.

2.5 Standards LTE Requirements

LTE is specified completely in 36 series technical specifications of 3GPP. The respective LTE Release 8 and 9 specifications, and LTE-Advanced as of Release 10 can be found on the web pages of 3GPP online in [22].

2.5.1 Data Performance

Figures 2.5 and 2.6 show the maximum theoretical peak data rates of cell per TTI that can be achieved in Release 8 LTE network under ideal conditions. The highest data rates in the

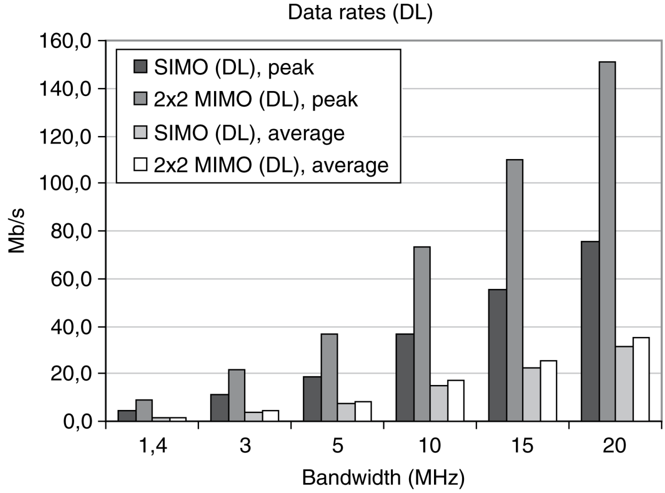

Figure 2.5 The theoretical peak and average data rates of LTE Release 8 in downlink.

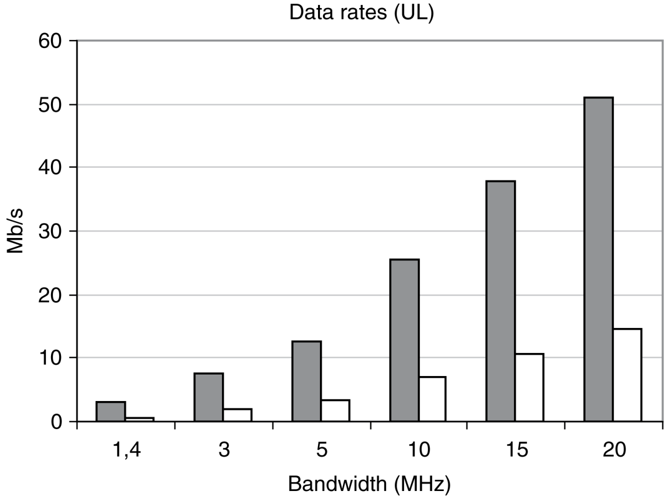

Figure 2.6 The theoretical peak and average data rates of Release 8 LTE in uplink.

Table 2.3 Key characteristics of LTE-UE classes.

Functionality	Class 1	Class 2	Class 3	Class 4	Class 5
Peak data rate in downlink (Mb/s)	10	50	100	150	300
Peak data rate in uplink (Mb/s)	5	25	50	50	75
Modulation in downlink	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM
Modulation in uplink	QPSK, 16-QAM	QPSK, 16-QAM	QPSK, 16-QAM	QPSK, 16-QAM	QPSK, 16-QAM, 64-QAM
MIMO in downlink	optional	2 × 2	2 × 2	2 × 2	4 × 4
MIMO in uplink	no	no	no	no	no

20 MHz bandwidth are a result of the clearly improved spectral efficiency compared to the previous systems. These figures are applicable to the situation with the LTE-UE close to the eNodeB (within 20% of the maximum radius), and the terminal located in a noise-limited environment. The layer 1 net data throughput has been taken into account as defined in TS 36.213, with 64-QAM in downlink and 16-QAm in uplink.

In the dimensioning of the network, the available capacity depends on the overhead. With a typical traffic profile, the overhead can be about 50% for small packets (60 bytes), 25% for medium-sized and large packets (600/1500 bytes). The radio interface overhead is due to the PDCP and RLC, and represents about 5%. The transport overhead in turn depends on the use of the IPSec, being approximately 25% with it and about 15% without it.

2.5.2 LTE-UE Requirements

The LTE-UE categories and respective capabilities are shown in Table 2.3 and Table 2.4. All the categories 1–5 support the frequency bandwidths up to the maximum possible of 20 MHz. Category 6 and 7 support a maximum of 40 MHz bandwidth (two carriers combined), and Category 8 supports 100 MHz (up to five carriers combined).

The reception diversity is mandatory for all classes. For the eNodeB, the transmission diversity is defined for 1–4 transmitter antennas. The 64-QAM modulation is not mandatory in the uplink direction for the UE classes 1–4, but otherwise both downlink and uplink should

Table 2.4 Additional key characteristics of UE classes. These form the LTE-Advanced access as of Release 10. Release 12/13 introduces also class 0 for M2M.

Functionality	Class 6	Class 7	Class 8
Peak data rate in downlink (Mb/s)	300	300	3000
Peak data rate in uplink (Mb/s)	50	100	1500
Modulation in downlink	Up to 64-QAM	Up to 64-QAM	Up to 64-QAM
Modulation in uplink	Up to 16-QAM	Up to 16-QAM	Up to 64-QAM
MIMO in downlink	2 × 2 or 4 × 4	2 × 2 or 4 × 4	8 × 8
MIMO in uplink	No	2 × 2	4 × 4

support all the modulation schemes from the set of QPSK, 16-QAM and 64-QAM. It should also be noted that downlink 2 × 2 MIMO is mandatory in classes 2–5.

In practice, the Category 3 devices were the default in the commercial markets until 2013, and the Category 4 devices have been introduced gradually since late 2013. The Class 3 has been the most popular LTE UE type since the first deployment in 2011. In 2013, Class 3, with a maximum theoretical DL data rate of 100 Mb/s was the default for the LTE user equipment, and the support of Class 4 with the maximum theoretical DL data rate of 150 Mb/s both in network and UE side started to be deployed in 2014 [30]. For the M2M devices, Class 1 has been the most suitable, and Release 12/13 defines for it class 0 to further optimize low data rates.

2.5.3 Delay Requirements for Backhaul

The QoS requirements of the transport network are principally determined by the services that the users demand and consume. The delay requirements are thus given for interactivity as well as for the response time, and also for the throughput performance if the connection is based on the TCP.

The delay requirements that are set by the radio network layer protocols are given for the handover and ANR in the *S1* and *X2* interfaces. As a comparison, the delay requirements for the *Iub* and *Iur* interfaces of the WCDMA system are based on the macro-diversity combining, outer loop power control, frame synchronization and packet scheduler.

Logically, the end user experiences the delay differently depending on the application. The use of, for example, video streaming, FTP or web browsing would require less rapid response times, more than 1 s delay being still acceptable for users. The quality of the video telephony or audio streaming would suffer from delays greater than 200 ms, the optimal value being around 100–200 ms. The most critical applications such as real-time gaming, video conferencing, video broadcast and machine-to-machine remote control would work well if the delay is between 20–100 ms.

The internal LTE handover which happens via the signaling of the direct *X2* interface between the eNodeB elements causes a 30–50 ms radio link interruption until the handover procedure has been completed. The data transmission is suspended during this time. If data is arriving from the network to LTE-UE, it is buffered accordingly. The effect of this should be taken into account in the network deployment by designing the latency in the *X2* interface equal or lower than the radio interruption time in order to avoid a bottleneck in this part. This is thus one of the optimization tasks of the operator. Figure 2.7 shows the principle of the LTE/LTE-A handover.

The capacity can be increased for the inter-eNodeB handovers when signaling via the *X2* interface. At the stage of activating the *X2* signaling, the source eNodeB fills the uplink path slightly more, if we assume asymmetric user traffic and symmetric backhaul capacity in both directions. On the other hand, the target eNodeB experiences a short increase in the downlink traffic at the same time, which is in practice still less than 2% on average. For this reason, the additional capacity is not needed in the typical cases of the deployment of the network. Nevertheless, the extra capacity should be considered in the areas where a high handover performance is required. Figure 2.8 clarifies the method.

The transport service attributes, that is, the values for the service level parameters, are typically driven by the user service requirements. The values depend on the overall situation of the network, but the following recommendations could be considered as general guidelines.

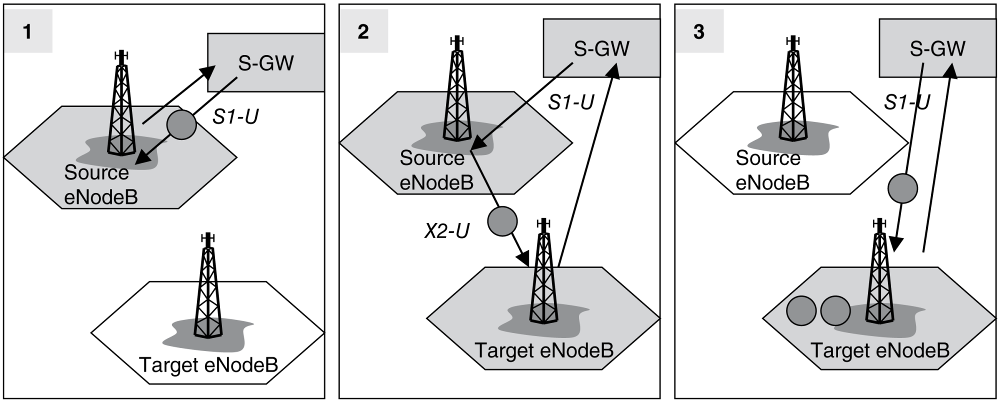
1
S-GW
S1-U
Source eNodeB
Target eNodeB
2
S-GW
S1-U
Source eNodeB
X2-U
Target eNodeB
3
S-GW
S1-U
Source eNodeB
Target eNodeB

Figure 2.7 The principle of the handover between two eNodeB elements.

- Packet delay (PD) is recommended to be equal to or less than 10 ms. It should be noted that in the user plane, the packet delay affects latency and throughput of the TCP type of services. In the control plane, the recommendation for the WCDMA to be equal to or less than 20 ms is still valid.
- Packet delay variation (PDV) is recommended to be equal to or less than ±5 ms. In the user plane, this value is recommended especially for the voice service. In the control plane, this

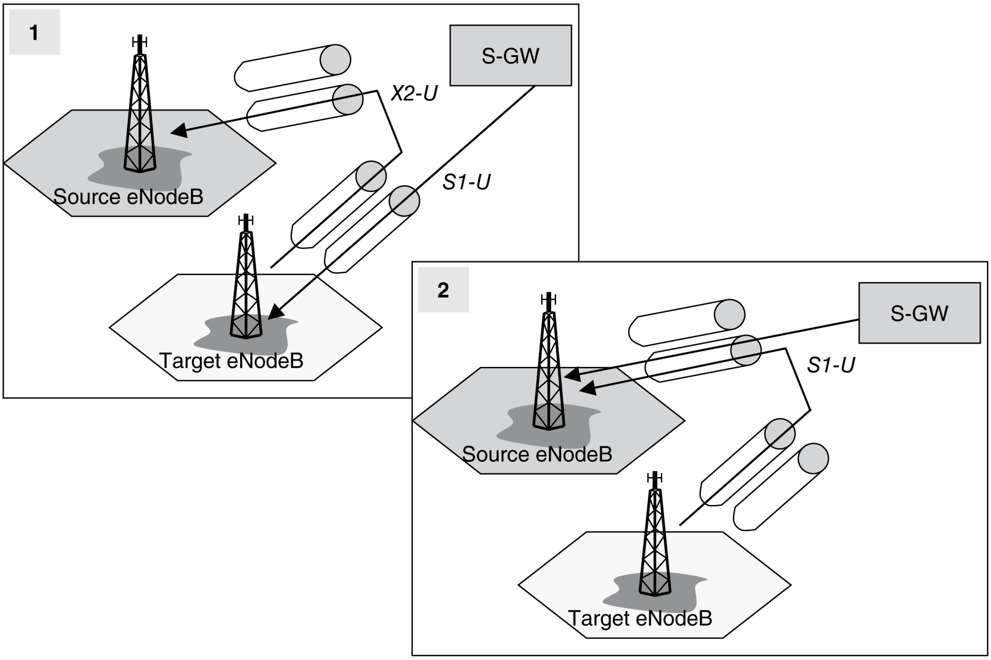
1
S-GW
X2-U
S1-U
Source eNodeB
Target eNodeB
2
S-GW
S1-U
Source eNodeB
Target eNodeB

Figure 2.8 The capacity can be increased for the *X2* handover purposes in the highest demand areas of LTE.

value is recommended for the timing over packet (ToP) concept, based on the IEEE 1588-2008 definitions.
- Packet loss ratio (PLR) is recommended to be equal to or less than 10^{-4}. It should be noted that in the user plane, the packet loss performance affects the throughput values of TCP-based services.

2.5.4 System Architecture Evolution

Also the system architecture requirements need to be created accordingly throughout the planned evolution of LTE. The System Architecture Working Group 2 thus initiated a study called System Architecture Evolution (SAE) with the aim of developing a framework for an evolution or migration of the 3GPP system to a higher-data-rate, lower-latency, and packet optimized system that supports multiple Radio Access Technologies. It should be noted that the focus of this work was set on the PS domain with the assumption that voice services are supported in this domain. SA2's SAE work was conducted under Work Item "3GPP system architectural evolution" that was approved in December 2004. It was initiated when it became clear that the future was clearly IP with everything (the "all-IP" network, AIPN, details can be found in TS 22.978 [31]), and that access to the 3GPP network would ultimately be not only via UTRAN or GERAN but by Wi-Fi, WiMAX, or even wired technologies.

The main objectives of the SAE study were to investigate:

- the impact on overall architecture resulting from RANs LTE work;
- the impact on overall architecture resulting from SA1's All IP Network concept;
- the overall architectural aspects resulting from the need to support mobility between heterogeneous access networks.

Figure 2.9 shows the evolved system architecture, possibly relying on different access technologies.

The new reference points were identified as listed below:

- *S1* provides access to Evolved RAN radio resources for the transport of user plane and control plane traffic. The *S1* reference point enables MME and UPE separation and also deployments of a combined MME and UPE solution.
- *S2a* provides the user plane with related control and mobility support between a trusted non-3GPP IP access and the SAE Anchor.
- *S2b* provides the user plane with related control and mobility support between ePDG and the SAE Anchor.
- *S3* enables user and bearer information exchange for inter-3GPP access system mobility in an idle and/or the active state. It is based on *Gn* reference point as defined between SGSNs.

User data forwarding for inter-3GPP access system mobility in the active state.

- *S4* provides the user plane with related control and mobility support between the GPRS Core and the 3GPP Anchor and is based on the *Gn* reference point as defined between SGSN and GGSN.
- *S5a* It provides the user plane with related control and mobility support between MME/UPE and the 3GPP anchor. It is FFS whether a standardized *S5a* exists or whether MME/UPE and 3GPP anchor are combined into one entity.

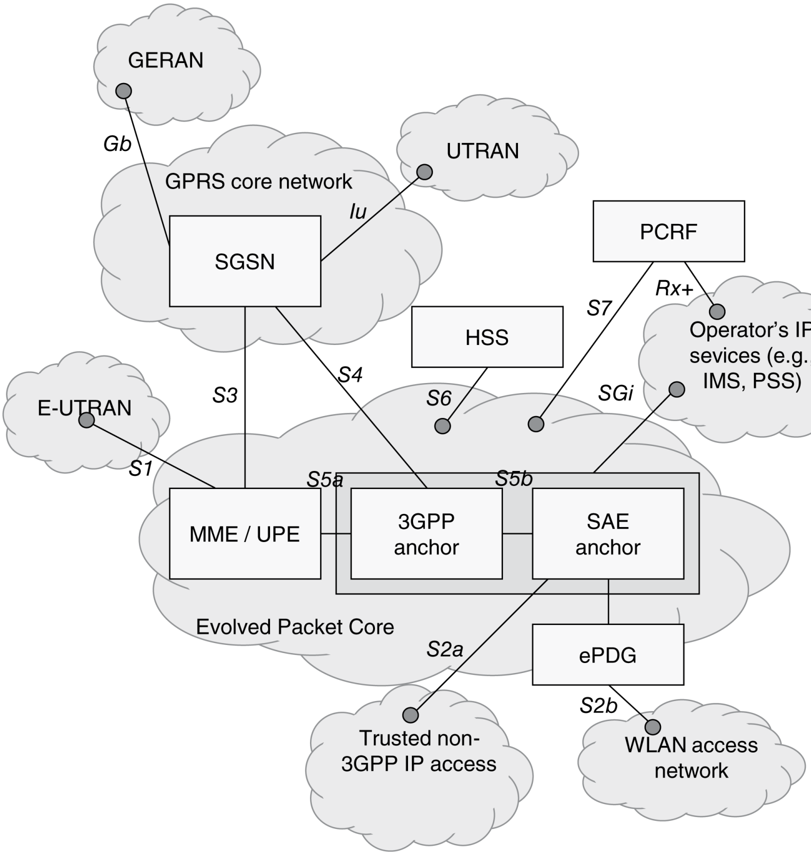
GERAN
Gb
GPRS core network
UTRAN
Iu
SGSN
PCRF
Rx+
S7
HSS
Operator's IP sevices (e.g., IMS, PSS)
E-UTRAN
S3
S4
S6
SGi
S1
S5a
S5b
MME / UPE
3GPP anchor
SAE anchor
Evolved Packet Core
S2a
ePDG
S2b
Trusted non-3GPP IP access
WLAN access network

Figure 2.9 The evolved packet system architecture.

- *S5b* provides the user plane with related control and mobility support between the 3GPP anchor and the SAE anchor. It is for further study whether a standardized *S5b* exists or whether 3GPP anchor and SAE anchor are combined into one entity.
- *S6* enables the transfer of subscription and authentication data to authenticate and authorize user access to the evolved system (the AAA interface).
- *S7* provides the transfer of (QoS) policy and charging rules from PCRF to Policy and Charging Enforcement Point (PCEP). The allocation of the PCEP is FFS.
- *SGi* is the reference point between the Inter AS Anchor and the packet data network. The packet data network may be an operator external public or private packet data network or an intra-operator packet data network, for example, for the provision of IMS services. This reference point corresponds to *Gi* and *Wi* functionalities and supports any 3GPP and non-3GPP access systems.

In order to re-use the earlier definitions, it was decided that the interfaces between the SGSN in the 2G/3G Core Network and the Evolved Packet Core should be based on the GTP protocol. The interfaces between the SAE MME/UPE and the 2G/3G Core Network will be based on the GTP protocol.

2.6 LTE Key Features

2.6.1 Release 8

According to 3GPP, the LTE Release 8 Key Features and requirements are the following:

- *High spectral efficiency*. This is done via the OFDM in the downlink, making the system robust against multipath interference and having high affinity with advanced techniques such as frequency domain channel-dependent scheduling and MIMO. In the uplink, DFTS-OFDM, or Single-Carrier FDMA, is used, which provides a low Peak-to-Average Power Ratio (PAPR) and the user orthogonality in the frequency domain. Also the multi-antenna application can also be used.
- *Very low latency* means that there is a short set-up time as well as short transfer delay. In addition, the handover latency and interruption time are short, as well as the TTI and RRC procedure. To support fast signaling, the RRC states are defined as simple.
- *Support of variable bandwidths* means that it is possible to define some of the following bands: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz.
- *Simple protocol architecture* means that the communication is based on a shared channel, and that there is only the packet-switched domain available, yet it is still capable of supporting also Voice-over IP calls.
- *Simple architecture* has been achieved by introducing eNodeB as the only E-UTRAN node. This leads to the smaller number of RAN interfaces, between the eNodeB and MME/SAE-Gateway (*S1*), and on the other hand, between two eNodeB elements (*X2*). Figure 2.10 presents the principle of the LTE/LTE-A radio network interfaces.

The benefit of the distributed solution of LTE is that the MAC protocol layer that takes care of the scheduling is present solely in the UE and in the eNodeB which provides fast signaling. This is essential in order to optimize the TTI (Transmission Time Interval), which is 1 ms in

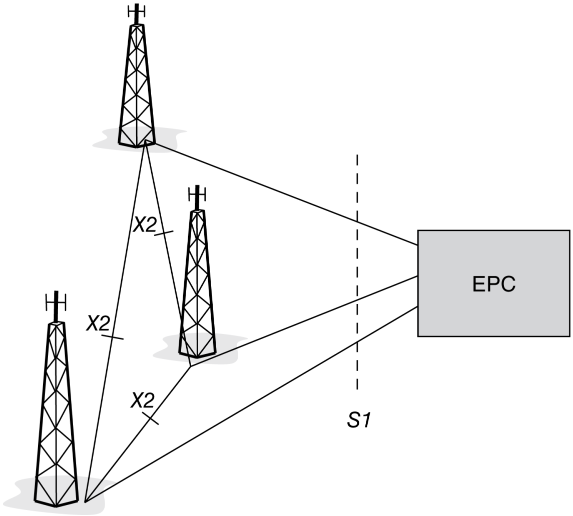

Figure 2.10 The radio network interfaces.

LTE. As a comparison, the MAC protocol layer and the scheduling of UMTS are found in the radio network controller, and along with the introduction of HSDPA an additional MAC sub-layer taking care of the HSPA scheduling was added in the W-CDMA NB.

The LTE TTI allows the eNodeB scheduler to be aware of the physical radio environment seen by each UE. They inform eNodeB about their received radio quality which the scheduler uses as a criterion for the selection of the Modulation and Coding scheme. The HARQ (Hybrid Automatic Repeat Request) together with soft-combining and rate adaptation thus provide fast adaptation to the variable conditions of the radio interface. The scheduler also takes care of the prioritization and QoS. Furthermore, the scheduler decides the radio resources per UE in DL and UL. Within each scheduled TTI per UE, the Transport Block (TB) transfers the user data via the transport channel. Compared to the previous releases, LTE simplifies the channel structure. Thus, only one shared transport channel is used in the DL and another in the UL as the services can be multiplexed into the same user plane bit stream.

The high spectral efficiency and optimal scheduling of LTE have been achieved through the use of the multi-carrier multiple access. The OFDMA (Orthogonal Frequency Division Multiple Access) is used in the DL and SC-FDMA (Single Carrier Frequency Division Multiple Access), that is, DFT (Discrete Fourier Transform) spread OFDMA in the UL, combining the optimal characteristics of each solution. Figure 2.11 presents the principle of OFDMA and SC-FDMA.

OFDM refers to a multi-carrier technology. It divides the bandwidth into multiple mutually orthogonal narrowband sub-carriers. In the OFDM Access (OFDMA) solution, the sub-carriers are shared for multiple users according to need. One of the most significant benefits of OFDM is its resistance to fast fading due to multi-path components, especially in urban areas where Rayleigh fading is dominant.

The drawback of OFDMA is the high Peak-to-Average Power Ratio (PAPR) which requires expensive power amplifiers due to their demanding requirements on linearity. This further increases the power consumption. These issues are not significant for the eNodeB element, but both would cause non-optimal costs and functionality for the user equipment. For this reason, an alternative solution was specified for the user equipment transmitter, that is, SC-FDMA.

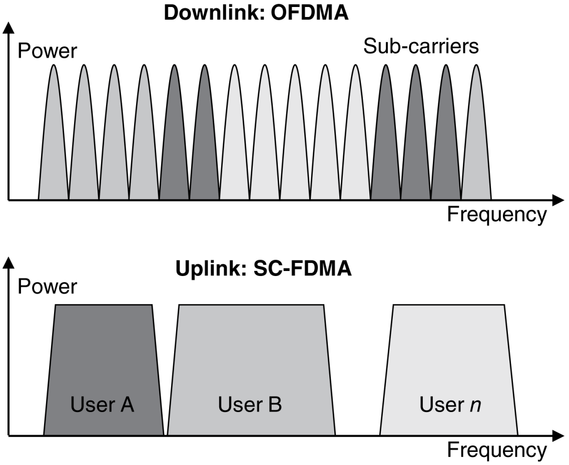

Figure 2.11 The principle of the DL OFDMA and UL SC-FDMA.

Table 2.5 The main LTE parameters.

Parameter	Value
Modulation	Selectable form QPSK, 16-QAM, 64-QAM
DL access scheme	OFDMA
UL access scheme	DFTS-OFDM (i.e., SC-FDMA)
Bandwidth	Selectable from 1.4/3.0/5.0/10/15/20 MHz
Minimum TTI	1 ms
Sub-carrier spacing	15 kHz
Cyclic prefix length	short: 4.7 us/long: 16.7 us
Spatial multiplexing	DL: maximum of 4 layers per UE UL: 1 layer per UE MU-MIMO for DL and UL

This results in signals comparable to a single carrier which leads to a low PAPR, simpler handset design and lower power consumption than OFDM would cause. In order to assure the fluent deployment at a global level, LTE specifications provide various RF bands and bandwidths. Furthermore, the specifications provide both FDD and TDD modes.

The essential functionality of LTE is its compatibility with the earlier 3GPP Releases, making the inter-working fluent. In addition, it has inter-working defined with other systems, for example, cdma2000. The LTE standard supports both FDD and TDD modes within a single radio access technology. There is also an efficient Multicast/Broadcast functionality included in the standard, which makes it possible to use a single frequency network SFN concept derived as an option that is available in OFDM.

LTE also supports the Self-Organizing Network (SON) operation, which can be highly efficient in the dynamic and automatic network tuning as a function of selected network performance indicators, including the feedback from the fault management. Table 2.5 shows the most important LTE Release 8 parameters and their values.

Thus, the first LTE Release 8 builds the basis for the evolved UTRAN which increases the data transfer performance and is taken into account also in the evolved system architecture. The essential features include OFDMA and SC-FDMA for DL and UL access, respectively, as well as layer 2 control radio connection management and handover control. The result of these enhancements provides 3-4-fold spectral efficiency compared to previous releases of W-CDMA [32].

2.6.2 *Release 9*

LTE, both the evolved radio as well as the evolved core, has been on the market since late 2010. Release 8 was frozen in December 2008, which is the basis for the first generation of the LTE equipment. The Release 8 LTE specifications are noted to be stable. In addition to the basic set of the Release 8 definitions, relatively small enhancements were introduced in Release 9, which was functionally frozen in December 2009 and completed in Spring 2010.

Release 9 introduces relatively minor enhancements. The respective LTE requirements for the performance have thus not been changed since the original set. Nevertheless, the set of Release 9 services is extended as can be seen in Figure 2.12 [32,33].

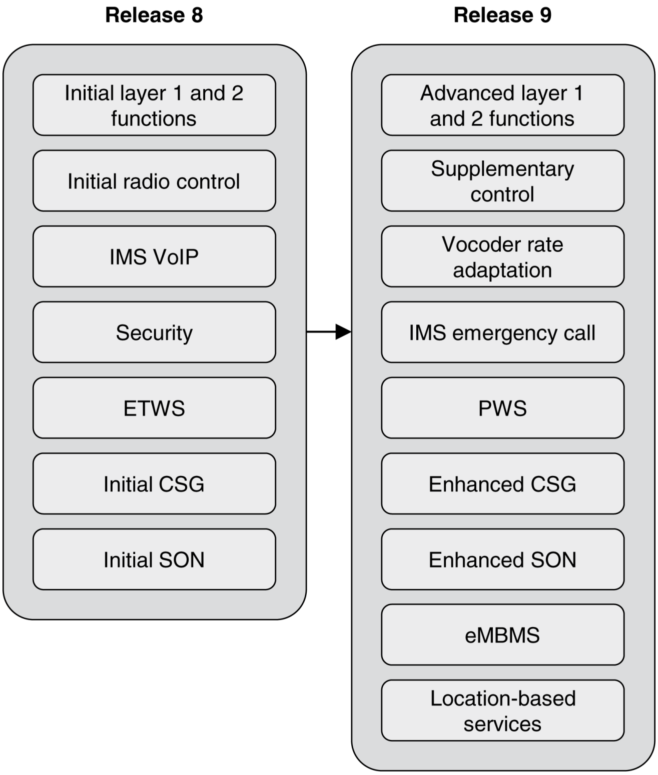
Release 8
Initial layer 1 and 2 functions
Initial radio control
IMS VoIP
Security
ETWS
Initial CSG
Initial SON
Release 9
Advanced layer 1 and 2 functions
Supplementary control
Vocoder rate adaptation
IMS emergency call
PWS
Enhanced CSG
Enhanced SON
eMBMS
Location-based services

Figure 2.12 A comparison of key items of Releases 8 and 9.

The main differences between Release 8 and 9 are:

- new Location-Based Services (LBS);
- extension to Closed Subscriber Group (CSG);
- extensions to Self-Organizing Networks (SON);
- enhancement for the Multimedia Broadcast Multicast Service (MBMS);
- Public Warning System (PWS);
- LTE-MIMO with dual-layer beamforming;
- enhancements for Home eNodeB concept with femto-cell.

Furthermore, Release 9 added, for example, frequency band options for FDD mode and RF requirements for multi-carrier and multi-RAT base stations.

2.6.2.1 Public Warning System (PWS) functions

As a result of various major emergency situations such as natural disasters and exceptionally severe accidents, including tsunamis, earthquakes, forest fires, and hurricanes, the regulative bodies have taken an increasing interest in assuring that the public has the means to receive relevant alerts and warnings in time. The focus has been to create a method that would not depend on the telecommunications technology.

There have already been emergency systems deployed via public radio and television broadcast networks, and the development has also included mobile networks. The latter is the logical next step to complete the overall infrastructure thanks to the broadcast features. Warning messages can thus be delivered to a large audience directly via the user devices that typically are personal and carried about by people.

For the further assurance of the functionality of the cellular broadcast features, the PWS principles have been developed to be used in emergency situations where life or property is at imminent risk, and where immediate responsive actions are expected. Some of the main requirements, for example, in the USA are the following:

- PWS should be able to broadcast warning notifications to multiple users simultaneously without need for acknowledgment.
- PWS should support concurrent broadcast of multiple warning notifications.
- There should be a means to broadcast the notifications within geographical areas.
- User equipment that supports the PWS should be able to receive the notifications also in Idle mode.
- The notifications should be processed by the user equipment according to the FIFO principle (first-in, first-out).
- The reception and presentation of the notifications should not interfere with the ongoing communications.

As a result, in the US markets, a Commercial Mobile Alert System (CMAS) has been developed. LTE initially supported CMAS already as of Release 8 to alert users. At that stage, the feature was called ETWS feature, that is, Earthquake and Tsunami Warning System. The PWS further extends the possibilities of ETWS as it provides support for multiple parallel warning notifications, can replace or cancel a warning notification, and repeat the warning notification with a repetition period of 2 seconds up to 24 hours.

The functionality of the CMAS is based on Cell Broadcast Center (CBC), which sends a warning message content to MME which forwards it to E-UTRAN. The warning message is broadcast in dedicated system information blocks. ETWS messages are found in SystemInformationBlockType10 and SystemInformationBlockType11.

The CMAS is introduced in 3GPP Release 9. It is capable of delivering multiple, concurrent warning notifications. The CMAS warning notification is broadcast in SystemInformationBlockType12. Paging is used in order to inform CMAS-capable user equipment about the message in both RRC_IDLE and RRC_CONNECTED state. Upon UE receiving the paging message with the CMAS indication, it starts receiving CMAS notifications based on the scheduling information list which is found in SystemInformationBlockType1. To comply with the requirements of replacing and cancellation of the notifications, additional procedures are included in LTE between MME and eNodeB.

2.6.2.2 LTE-MIMO with Dual-Layer Beamforming

Beamforming (BF) has been developed to enhance the LTE data rate, the system capacity and the radio coverage, and to finally increase the user experience especially at the cell edge. LTE Release 8 includes support for single-layer beamforming that is based on user-specific reference symbols, that is, dedicated RS, DRS or DM RS. The Single-layer beamforming is based on only a single codeword or transport block. Beamforming provides the possibility to direct the beam towards selected UE by using the eNodeB position estimation, that is, the direction of arrival. The beam is formed via an antenna element array and by applying a precoding similar to the data payload and the UE-specific reference signal within this beam. The UE-specific reference signal is transmitted in such a way that its time-frequency location does not overlap with the cell-specific reference signal.

There is no need for user equipment feedback which makes beamforming especially suitable for the LTE-TDD mode, relying on the reciprocity principle of downlink and uplink antennas. The 3GPP Release 9 further enhances DRS-based beamforming via multi-layer beamforming. The extension of the Release 8 single-layer beamforming to a multi-layer variant gives further tools, for example, for the 3G LCR-TDD operator to use the TDD-LTE network while continuing to use DRS based beamforming and leveraging the installed base of potentially existing antenna arrays.

2.6.2.3 eMBMS

Evolved MBMS (eMBMS) is an enhancement for the MBMS (Multimedia Broadcast Multicast Service) that was initially already specified in the Release 6 W-CDMA system. It is designed to broadcast information to multiple users by sharing the same broadcast channel. The service is useful, for example, for the reception of advertisement and news. Furthermore, the service provides the possibility of creating a closed group, for example, for streaming payable TV content. As the service is integrated to the system, no additional frequency spectrum is required. The benefit of eMBMS is the capacity saving, as the same infrastructure is used for all users and no acknowledgment messaging is needed per user. Nevertheless, eMBMS provides the possibility to use the uplink capacity for interactions.

The default assumption of the 3GPP specifications was to keep the impact of the introduction of the MBMS on existing infrastructure as low as possible. This was done by designing only one additional network element with minimal signaling with other elements. Figure 2.13 summarizes the network architecture for the MBMS service in GSM and UMTS networks. In this environment, NodeB elements take care of the MBMS control and physical carriers, the Radio Network Controller (RNC) manages the bearers and service area selection, the SGNS (Serving GPRS Support Node) manages the bearers and updated RNC signaling, the GGSN (Gateway GPRS Support Node) manages bearers and a new interface to BM-SC as well as join and leave procedures, and finally, the BM-SC (Broadcast/Multicast Service Center) manages the authentication, charging, and service scheduling.

As LTE further simplifies the network architecture, also the introduction of eMBMS over LTE needs to be simple. Figure 2.14 presents the LTE architecture for the eMBMS service.

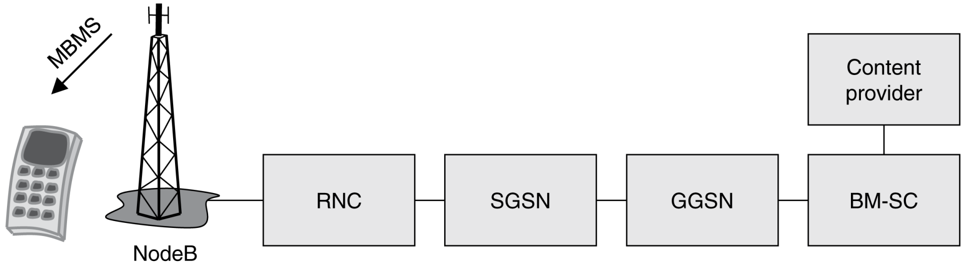

Figure 2.13 The MBMS architecture for pre-LTE networks, that is, for GSM and UMTS systems.

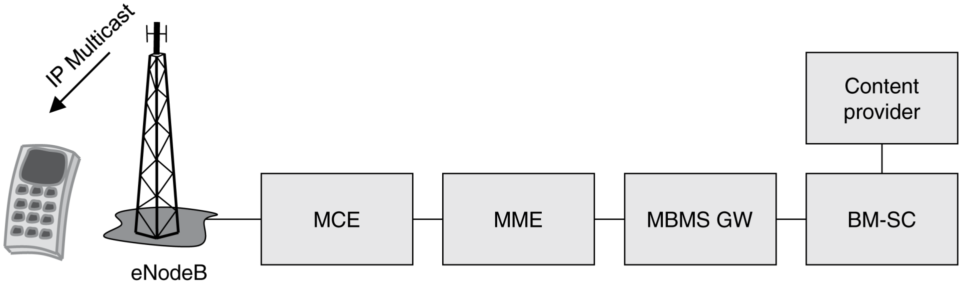
IP Multicast
eNodeB
MCE
MME
MBMS GW
BM-SC
Content provider

Figure 2.14 The eMBMS architecture in LTE/LTE-A.

In addition to the modifications as indicated in Figure 2.15, the support of eMBMS in LTE requires new logical, transport and physical channels. The eMBMS architecture is divided into three domains:

- User Equipment (UE). This domain has the equipment employed by the user to access the MBSFN services in Single Frequency Network areas.
- Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). Within this domain, eNodeB elements collect the eMBMS-related information and further transmit it to users over the air-interface.
- the Evolved Packet Core (EPC).

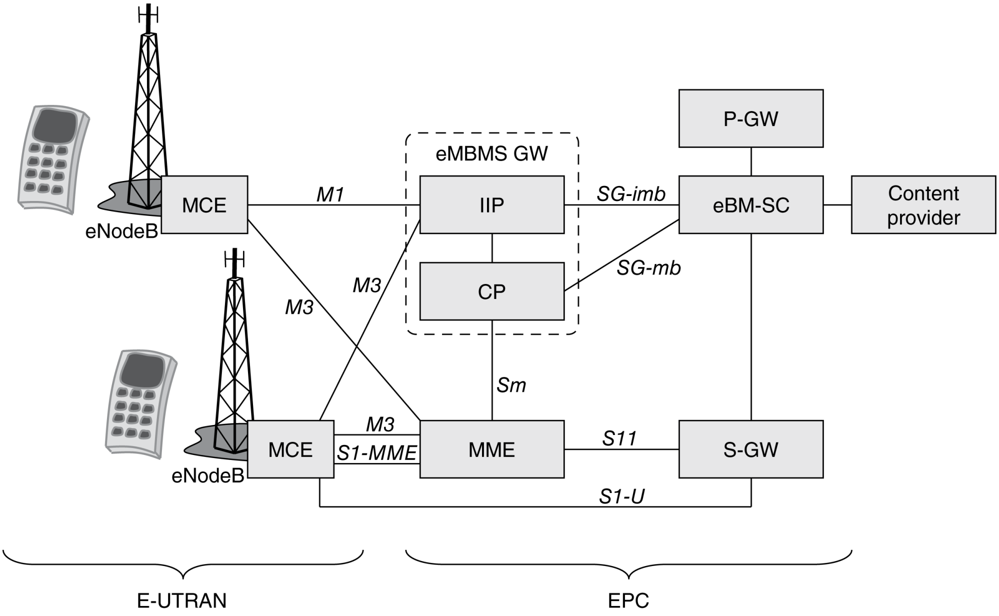
P-GW
eMBMS GW
MCE
M1
IIP
SG-imb
eBM-SC
Content provider
eNodeB
CP
SG-mb
M3
M3
Sm
M3
MCE
S1-MME
MME
S11
S-GW
eNodeB
S1-U
E-UTRAN
EPC

Figure 2.15 The new eMBMS architecture for LTE networks.

Figure 2.15 presents a more detailed architecture and the interfaces of the eMBMS of LTE/LTE-A. The Multi-cell/multicast Coordination Entity (MCE) coordinates the transmission of signals that are synchronized between cells. It also manages the allocation of the time and frequency radio resources for the eNode B elements that are located in the MBSFN area for multi-cell MBMS transmissions. Furthermore, MCE manages the radio configuration, including the selection of the MCS.

As can be seen in Figures 2.14 and 2.15, the heart of the eMBMS service is the eBM-SC (Evolved Broadcast/Multicast Service Center). It was defined already in 3GPP Release 6, and was called the BM-SC, as seen in Figure 2.13. The tasks it performs are authentication, authorizing content provider, charging, and the configuration of the data flow through the core network [33]. Another element is the MBMS Gateway (MBMS GW). It is a logical node and takes care of the IP packet multi-casting from the BM-SC element to the eNodeB element of LTE. It also manages the session control via the MME element.

Another eMBMS element is the MCE (Multi-cell/Multicast Coordination Entity). It coordinates the resources and transmission parameters of the cells within the respective MBMS Single Frequency Network area (MBSFN). The MCE can be integrated physically into eNodeB, typically by executing a software upgrade to the existing hardware. The drawback of this solution is that only cells that belong to that particular base station can form a MBSFN, so the MCE can also be built as a separate element.

Figure 2.16 shows an example of the eMBMS deployment. The Multicell/multicast coordination entity manages the synchronized data delivery in eMBMS single frequency network. The MBSFN defines certain geographical areas where the transmission is done in the same frequency. The contents are scheduled by MCE. The broadcast refers to "everyone" while multicast refers to a certain group within the defined eMBMS area, to which the users need to subscribe prior to receiving the multicast contents.

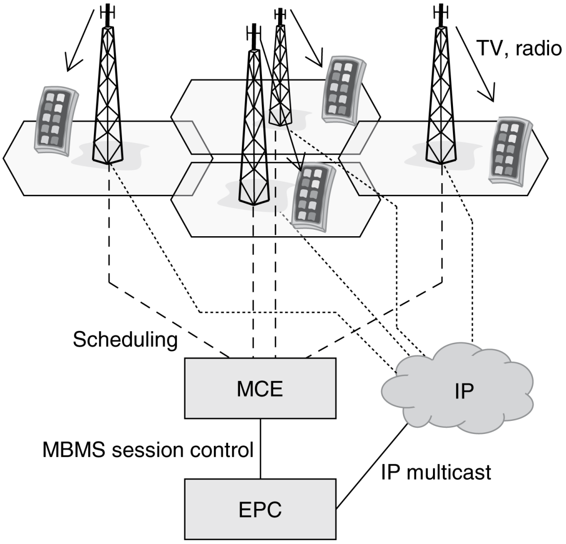

Figure 2.16 The high-level functionality of eMBMS.

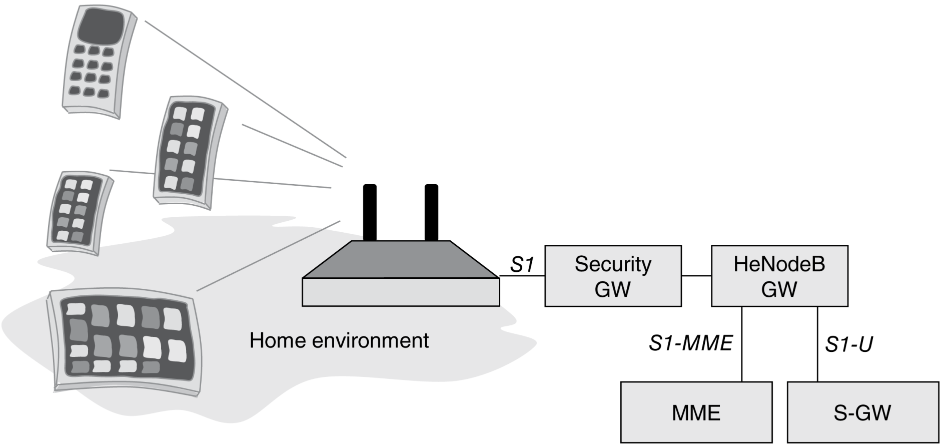

Figure 2.17 Home eNodeB architecture.

2.6.2.4 Home eNodeB Extensions

HeNodeB elements (Home eNodeB) provide additional coverage indoors, and they are meant for both home and office environments [34]. The HeNodeB refers to low-power eNodeB to create small cells, that is, femto cells. Typically the customer owns and operates the HeNodeB element. It is thus deployed without an operator and without prior radio network planning, yet it is connected to the operators' EPC (Evolved Packet Core).

The 3GPP LTE femto-cell is thus a synonym for Home eNodeB (HeNB). It is defined in 3GPP Release 9 LTE specifications. Nevertheless, the previous 3G femto cells have already been deployed at a global level to create residential, enterprise, and outdoor hotspots meant for low-power access points which enhance radio coverage and increase capacity. New requirements were designed in Release 9 due to the special characteristics of LTE.

Figure 2.17 shows the femto deployment scenario in a home environment. The role of the HeNodeB GW is to concentrate the signaling of the C-Plane in the *S1-MME* interface. There are two options: The *S1-U* interface of HeNodeB may be terminated at the HeNB GW, or a direct logical U-Plane connection between the HeNB and S-GW may be used. It should be noted that the *X2* connectivity between HeNBs is not supported although it is standardized in eNodeB interconnection.

2.6.2.5 Extension to CSG

The basis for the Closed Subscriber Group was defined in Release 8. It provides a mechanism to limit the cell access rights according to the users' group definitions. Via this functionality, it is possible to provide access to, for example, only family members for a Home eNodeB that has femto BTS installed. Femto BTS refers to a very small-power and small-size base station providing a coverage area of some tens of meters of radius.

The idea of the CGS functionality is to store a list of permitted access IDs to the LTE UE. The cells broadcast the IDs, and if the CSG ID is not found in the respective list in Idle mode, in Release 8 LTE, it is not considered a potential candidate. Release 8 also provides a solution for UE to perform an autonomous search for CSG based on arbitrary fingerprint information. As a result, Release 8 provides access only to the users belonging to the CSG list. The disadvantage was that the solution may cause interference with the operator's network depending on the radio wave propagation conditions and location of the Home eNodeB.

This functionality has been enhanced in Release 9 which provides the possibility to operate in hybrid access mode. This means that the Home eNodeB cell may broadcast a flag-bit which indicates whether also users within the cell coverage not belonging to the CSG group can access the network via the cell, for example, visitors at home or in the office. In other words, the users belonging to the CSG ID list, such as employees in the office or family members at home, can use the closed group functionality with the highest QoS, while other users experience the cell as a normal, open-access cell with lower QoS. If the user is found in the CSG ID list, the UE does an autonomous search and can prioritize the camping at CSG cells, and also the QoS for that UE can be prioritized. Meanwhile, the Release 8 UEs see the hybrid-access cells as normal ones without recognizing them as CSG cells. Even the Release 8 UEs cannot take advantage of the enhanced Release 9 functionality, the basic access is still guaranteed.

Release 9 also enhances the handover between CSG and normal cells while the CSG functionality is only possible in Idle mode in the case of Release 8. The latter does not thus provide handover with access control in connected mode from normal cell to CSG cell. Release 8 also may experience problems if the handover is done between two CSG cells because the eNodeB taking care of the handover does not have the means to distinguish between the other eNodeB identity (PCI, Physical Cell Id). This has been identified as a potential challenge, as the penetration of the Home eNodeBs will increase. Thus, a new procedure for the handover for these cases is implemented in Release 9 [19].

2.6.2.6 The Challenge of HeNodeB Elements

The "random" nature of the HeNodeB element deployment by the customers, combined with the potentially high number of HeNodeB elements in unpredictable geographical areas were already identified as a challenge in 3GPP Release 8 Technical Report 25.820 [17]. Based on this discussion, Release 9 has taken these challenges into account by defining concrete RF requirements for HeNodeB elements.

One of the most significant challenges is the handling of interference between macro cells and the HeNodeB elements. To cope with this challenge, interference reduction techniques in both the uplink and the downlink have been discussed in 3GPP technical reports on LTE FDD and LTE TDD.

The Home eNodeB is characterized by requirements derived from femto cell scenarios. To limit the interference from the HeNodeB elements to the macro eNodeB elements, the transmitter output power of the HeNB has been limited to +0 dBm for one transmit antenna port, +17 dBm for two transmit antenna ports and +14 dBm for four transmit antenna ports. On the other hand, in order to minimize the interference caused by the Home BS, it has to adjust the TX output power on adjacent channels licensed to other operators in the same area while optimizing coverage.

The solution for interference monitoring could be that the HeNodeB element uses its own receiver to evaluate the uplink interferences and measures the received interference power. Thus, a nearby UE transmitting to a macro eNodeB could be identified. In addition, [31] defines different RF requirements for HeNB compared to other types of base stations, that is, local area or wide area BS. These are mainly lower maximum output power, lower dynamic range, larger unwanted and spurious emission levels, lower inter-modulation requirements or more relaxed frequency error and sensitivity levels. Accordingly, new conformance test cases have been added in [35].

2.6.2.7 Extension to SON

Release 9 defines several enhancements to the Self Optimizing Network concept. These are related to mobility load balancing, mobility robustness optimization and random access optimization [32].

The mobility load balancing refers to the distribution of traffic load in such a way that the occurring handovers and cell re-selection are optimized, based on the load status of the respective eNodeBs involved in these procedures. As a basis for this, Release 9 defines the means of exchanging information about the load status, such as the amount of physical resource blocks (PRB), the load of backhaul, the eNodeB hardware load, and the cell capacity class (relative capacity indicator of involved cells). Also the exchange of the handover and cell re-selection parameter values may be done for further automatic value adjustments. In addition, the load balancing between LTE and other 3GPP radio access technologies can be supported via Release 9.

The mobility robustness optimization is defined for the potential handover failure cases in order to provide a better means to still recover the connection. When handover failure occurs, LTE tries to re-establish the connection via an available functional cell. Release 9 provides the means for this selected eNodeB to request the UE to state which NodeB it was when the failure occurred. Furthermore, the target eNodeB and the source eNodeB may now exchange information about the failure and adjust the handover parameter values (thresholds, timers) to increase the probability of success.

The random access optimization refers to the parameter value optimization related to the RACH (Random Access Channel). As was the case in previous 3GPP radio access technologies, the loaded RACH increases the collision probability of different access requests, which increases the retransmission requests. In LTE, also the very low utilization of the RACH wastes capacity as the resources need to be reserved. Release 9 solves this dimensioning problematic based on a new procedure for the UE – eNodeB reporting about the recent successful RACH attempts and collisions that the UE has detected.

SON is discussed in more detail in Chapter 10.

2.6.2.8 New LCS Functions

The location-based service (LBS) is a fast growing area. It is essential for increased safety aspects, and it also is useful in one's daily life as it gives high added value when finding routes and addresses. Release 9 adds the following location-based services:

- Assisted Global Navigation Satellite System (A-GNSS).
- Observed Time Difference of Arrival (OTDOA).
- Enhanced Cell ID (E-CID).

A-GNSS is based on the satellite navigation system information from, for example, GPS, GLONASS or GALILEO in such a way that the data is received by the UE directly via satellites as well as via the network. This set is used to calculate the accurate position of the UE. The final position may be calculated by the UE (UE-based positioning) or a server residing on the network side (UE-assisted positioning). OTDOA is based on the reference signal sent by

Table 2.6 Options for the location-based services in LTE/LTE-A in Release 9.

Method	UE-based	UE-assisted	eNB-assisted	Release
A-GNSS	Yes (UE measures and estimates)	Yes (UE measures, LC estimates)	No	Release 9
OTDOA, downlink	No	Yes (UE measures, LC estimates)	No	Release 9
Enhanced Cell ID	No	Yes (UE measures, LC estimates)	Yes (eNodeB measures, LS estimates)	Release 9

eNodeBs to UE, and the respective time difference information of arrival of the UE signal received by various eNodeB elements. The accurate location of the UE is calculated via the intersections of the distance circles between the eNodeBs and UE. E-CID, in turn, is based on the timing signal propagation delay calculated and the Angle of Arrival (AoA).

Along with the new location services, Release 9 also defines two new control plane application protocols, LPP (LTE Positioning Protocol) and LPPa (LPP annex). LPP is used between the UE and the E-SMLC (Enhanced Serving Mobile Location Center), and LPPa is defined between eNodeB and E-SMLC. In order to provide the possibility of implementing also the non-3GPP positioning protocols, the E-SMLC is located in the core network in the Release 9 network, whereas the location center traditionally was found in the radio network prior to Release 9 networks. Thus, for example, SUPL (OMA Secure User Plane Location) can be transmitted over LPP. Table 2.6 summarizes the Release 9 LBS options.

2.6.3 Release 10

2.6.3.1 4G Requirements

Release 10 brings for the first time the LTE into the level which complies with the ITU requirements for the fourth generation of mobile technologies via LTE-Advanced.

ITU's Radiocommunication Sector (ITU-R) defines the fourth generation requirements under the term IMT-Advanced. More specifically, the ITU-R Working Party 5D is charged with defining the IMT-Advanced global 4G technologies. The ITU Radiocommunications Assembly approved the ITU-R 229-2/5 questions on the future development of IMT-2000 and systems beyond IMT-2000. Those questions are about the general objectives, as well as technical, operational and spectrum issues for the systems of IMT-2000 and beyond. An essential step in the respective process was the production of a recommendation on the framework of the future development of the systems of IMT-2000 and beyond, that is, ITU-R Rec. M.1645.

ITU's Radiocommunication Sector (ITU-R) completed the assessment of six candidate submissions for the global 4G mobile wireless broadband technology on 21 October 2010. The harmonization among the proposals resulted in two technologies, "LTE-Advanced" (developed by 3GPP as LTE Release 10 and beyond under the name LTE-Advanced) and "WirelessMAN-Advanced" (developed by IEEE as the WirelessMAN-Advanced specification incorporated in IEEE Standard 802.16 beginning with the approval of IEEE Standard 802.16 m) being accorded the official designation of IMT-Advanced, which qualifies them as official 4G technologies on behalf of ITU. These technologies successfully met all of the

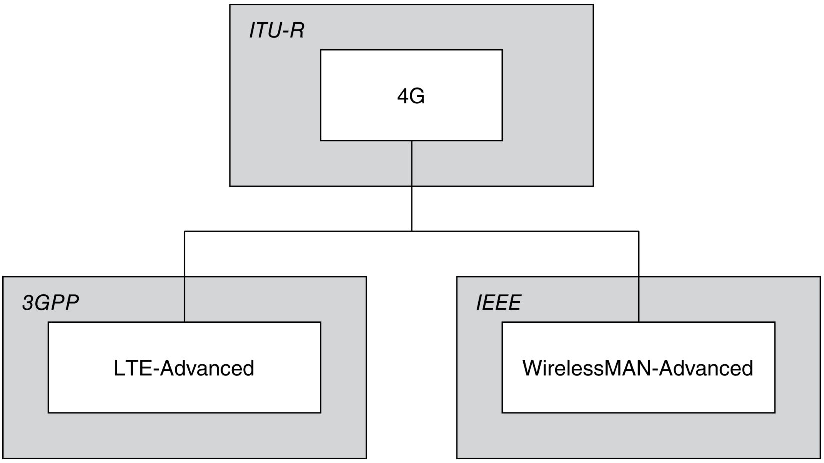

Figure 2.18 The current 4G technology field is divided between the 3GPP and IEEE solutions that comply with the ITU-R requirements for the fourth generation of mobile communications.

criteria established by ITU-R for the first release of IMT-Advanced. Figure 2.18 shows the current situation in the 4G field.

Following the success of the ITU-defined IMT-2000 (3G) systems, ITU-R launched the IMT-Advanced (4G) initiative with its strategic IMT future vision in 2002 [35]. It subsequently established the services, spectrum, and performance requirements for IMT-Advanced as well as a detailed evaluation process. In partnership with the industry, the six proposals received by ITU in October 2009 were evaluated against the requirements. Industry consensus and harmonization fostered by ITU-R among these six proposals have resulted in the consolidation of the proposals into two agreed IMT-Advanced technologies. These technologies moved into the final stage of the IMT-Advanced process, which produces the development of the LTE-Advanced.

IMT-Advanced has been defined in order to provide a global platform on which to build the next-generations of interactive mobile services that will result in faster data access, enhanced roaming capabilities, unified messaging and broadband multimedia.

The high-level definition of ITU for the Next Generation Network (NGN) from December 2004, which today is called IMT-Advanced, is the following [36]:

> An NGN is a packet-based network able to provide telecommunication services and able to make use of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies. It enables unfettered access for users to networks and to competing service providers and/or services of their choice. It supports generalized mobility which will allow consistent and ubiquitous provision of services to users.

The more specific LTE-Advanced requirements are the following, according to [37]: “Systems beyond IMT-2000 will be realized by functional fusion of existing, enhanced and newly developed elements of IMT-2000, nomadic wireless access systems and other wireless systems, with high commonality and seamless inter-working.” This means that 4G is actually a mix of various interacting systems, not only one single standard.

The targeted data rates of 4G, with wide area coverage and a significant mobility are in the range of 50–100 Mb/s. The definition of the 4G system states that it is a completely new fully IP-based integrated system of systems and network of networks achieved after the convergence of wired and wireless networks as well as computers, consumer electronics, and communication technology and several other convergences that will be capable of providing 100 mbps and 1 Gbps, respectively in outdoor and indoor environments, with end-to-end QoS and high security, offering any kind of services at any time as per user requirements, anywhere with seamless interoperability, always on, affordable cost, one billing and fully personalized.

The technical requirements for the Beyond IMT-2000 system are:

- high data rate transmission: for example, DL: 100 Mbps/UL: 20 Mbps;
- larger system capacity: for example, while 3G provides 1.2 Mb/s in 1 MHz band and 6-sector-BTS, 4G offers that 5–10 times more efficiently;
- lower cost/bit;
- wireless QoS control: NRT Service, RT Service, Multi-Cast Service.

In order to provide the services with the new data rates and lower latencies, the suitable radio technologies for B3G systems are:

- MIMO (Multiple-Input Multiple Output).
- Link adaptation techniques.
- Multi-carrier based modulation and access (OFDM/OFDMA).
- Iterative (multi-user) processing.
- “Cross-layer” optimization and design principles.
- Possibly Ultra-Wide Band (UWB).

In order to function in an optimized manner, the 4G networks might require, for example, the following high-level items:

- wider frequency bandwidth than in previous systems;
- truly global mobility and service portability;
- spectrally more efficient solutions such as modulation schemes;
- completely digital networks to fully use IP and converged video and data.

Figure 2.19 summarizes the key aspects of 4G, and Table 2.7 shows the comparison of the most essential performance-related items of 3G and 4G.

2.6.3.2 Release 10 Functionalities

The LTE Releases 8 and 9 are designed for a wide area deployment. The assumption for these releases is the macro layer for eNodeB elements, with dual receiver capability, single transmit antenna devices that function in a single RF band. For a typical use, the LTE-A defined as for Release 10 does not provide a significant performance improvement as it does not include new technologies as such. The standardization strategy has thus been to develop new enhanced features and technologies in order to extend the capabilities of LTE. Also, the standards focus on the support of new ways to deploy and operate the network in such a way that the services can be distributed optimally.

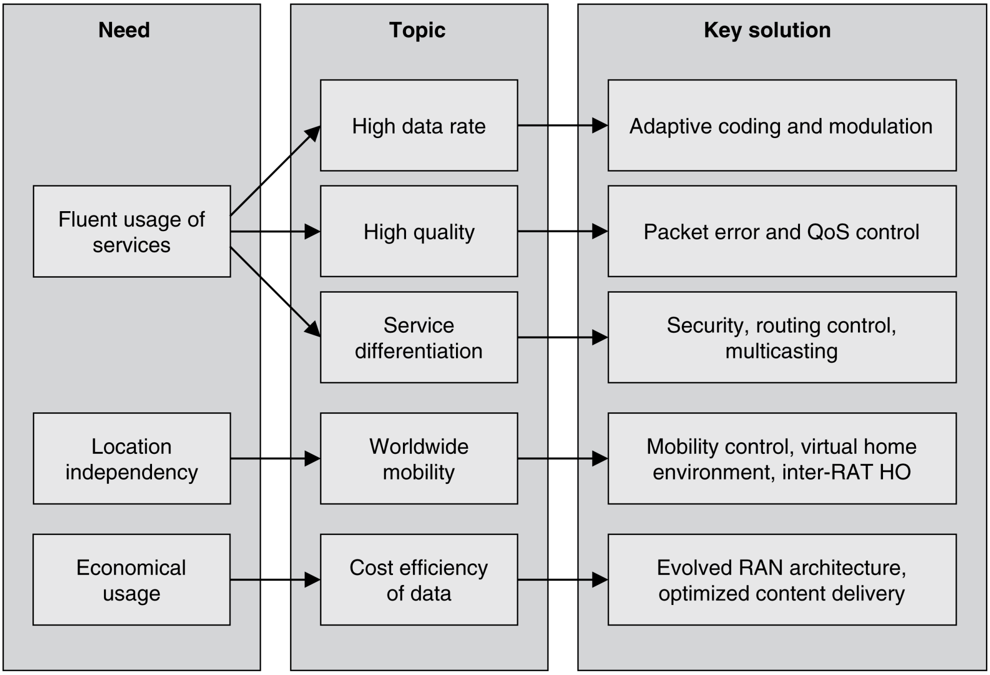
Need
Topic
Key solution
Fluent usage of services
Location independency
Economical usage
High data rate
High quality
Service differentiation
Worldwide mobility
Cost efficiency of data
Adaptive coding and modulation
Packet error and QoS control
Security, routing control, multicasting
Mobility control, virtual home environment, inter-RAT HO
Evolved RAN architecture, optimized content delivery

Figure 2.19 The high-level demand and solutions of the 4G.

LTE-A provides enhancements in both uplink and downlink via MIMO, coordinated multi-cell transmission and reception (CoMP), carrier aggregation (CA), relay nodes (RN) and heterogeneous network deployments (HetNet). These methods offer performance improvements in peak data rates, average spectrum efficiency, cell edge performance and coverage. They also provide a cost reduction for the deployment and operations of the networks via small base stations, and with cells that are lacking fixed transport connections.

Figure 2.20 summarizes the main functionalities that form the LTE-Advanced.

Table 2.7 Comparison of the main characteristics of 3G and 4G systems.

Topic	3G	4G
Priority	Voice as priority, and data as secondary	Data as priority, VoIP being only as one application for voice
Data rate	384 kb/s – 2 Mb/s (UMTS), up to 14 Mb/s in DL (HSDPA) and 5.8 Mb/s in UL (HSUPA), up to 84 Mb/s in DL and 22 Mb/s in UL (HSPA+)	1 Gb/s (DL) 500 Mb/s (UL)
Switching method	Circuit and packet switched	Packet switched
Frequency band	900 MHz – 2.5 GHz, possibly for 450 MHz	600 MHz – 8 GHz
Bandwidth	5 MHz (UTRAN) 1.4 – 20 MHz (E-UTRAN)	Up to 100 MHz

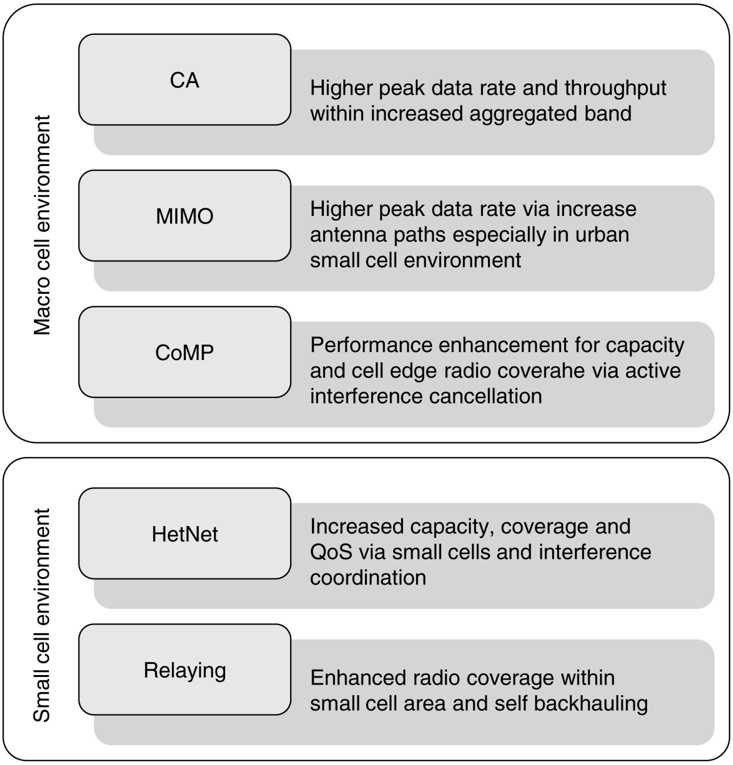
Macro cell environment
CA
Higher peak data rate and throughput within increased aggregated band
MIMO
Higher peak data rate via increase antenna paths especially in urban small cell environment
CoMP
Performance enhancement for capacity and cell edge radio coverahe via active interference cancellation
Small cell environment
HetNet
Increased capacity, coverage and QoS via small cells and interference coordination
Relaying
Enhanced radio coverage within small cell area and self backhauling

Figure 2.20 The main components that can be used in order to reach the required performance of LTE-Advanced.

2.6.3.3 RF Bands

LTE-Advanced considers the use of bandwidths of up to 100 MHz in the following spectrum bands, in addition to the ones that are already allocated for LTE [6]:

- the 450–470 MHz band. This band has already been identified in WRC-07 for use in the global environment for IMT systems.
- the 698–862 MHz band. This band has been identified in WRC-07 for Regions 2 and 3.
- the 790–862 MHz band. This band has been identified in WRC-07 for Regions 1 and 3.
- the 2.3–2.4 GHz band. This band has been identified in WRC-07 for global IMT systems.
- the 3.4–4.2 GHz band. More specifically, the 3.4–3.6 GHz band has been identified in WRC-07 for various countries.
- the 4.4–4.99 GHz band.

Section 2.5.2 and chapter 5 present more details on the LTE/LTE-A band scenarios.

2.6.3.4 Carrier Aggregation

Carrier Aggregation of LTE-Advanced makes it possible to combine up to five carriers, as specified in Release 8. The result of the CA is the increased transmission bandwidth and an enhanced data rate. It provides a high throughput without wide contiguous frequency band allocations. It also results in statistical multiplexing as the traffic is distributed dynamically over multiple carriers. Furthermore, CA may be used also in asymmetrical bands.

2.6.3.5 MIMO

MIMO (Multiple Input, Multiple Output), or multi-antenna solution refers to the transmitting and receiving via various antennas while using uncorrelated radio channels for the radio signals.

LTE Releases 8 and 9 already support the MIMO concept for up to four transmitter and receiver antennas in the downlink. Nevertheless, only a single antenna transmission can be used in the uplink direction. Release 10 widens the options for the MIMO, providing up to eight transmitting and receiving antennas in the downlink. Furthermore, Release 10 provides the possibility to use the uplink MIMO with up to four transmitting and eight receiving antennas. The increased degree of MIMO has a direct impact on the increased data rates.

In addition to the physical antennas, Release 10 also contains an enhancement for the reference signal design. In the downlink, the enhanced functionality includes user-specific reference symbols for signal demodulation and common reference symbols for the feedback. In the uplink, a more orthogonal reference signal structure is applied. These enhancements ensure a better performance especially for the highest number of antennas.

2.6.3.6 CoMP

Coordinated multipoint transmission and reception (CoMP) is designed to enhance the LTE/LTE-A cell edge performance as well as the system capacity. Nevertheless, this technology was considered still immature at the stage of Release 10.

There have been various CoMP variants under study, such as Coordinated Scheduling and Coordinated Beamforming (CS/CB), Joint Processing and Dynamic Cell Selection (JP/DCS), and Joint Processing and Joint Transmission (JP/JT). According to [38], the results of simulations and field tests indicate that CoMP may offer benefits especially from the single user point of view but at the same time, the efforts are not completely understood for the operation of large-scale networks. Also the impact of signaling between the UE and the network has not yet been modeled in the most realistic way, in order for the investigations to characterize the radio environment for multi-site transmission, so there are still open issues to be solved before any final conclusions are reached.

The general note of [38] is that the signaling needs to provide sufficient information to enable high performance, but the effect of the excessive overhead or additional energy and radio resource consumption must also be well understood before the final statements. CoMP has been identified as one of the items that can be used in the further enhancement of the LTE-Advanced performance and operations.

2.6.3.7 Relay Nodes

Relay nodes offer the possibility of the deployment of small cells at locations that are challenging, for example, in areas without a legacy of fixed or radio transmission backhaul.

Relay nodes may be based on the radio interface of LTE-Advanced in order to provide an "integrated" backhaul, via the Donor eNodeB element.

The highest benefit of the relay node can be achieved in limited coverage cases that consist of large donor cells serving various relay nodes. These relay nodes create a wider radio coverage area. These locations may be remote rural areas or indoors, and other locations that otherwise experience outage areas.

The relay node concept contains, as do many other 3GPP items, an evolution path. The first relay node definitions for LTE can be found in Release 8 which defines a first step approach which is basically a repeater amplifying and forwarding the radio signal. This solution as such is useful for radio coverage area extension though the drawback of this solution is that the radio resources cannot be utilized efficiently. The LTE-Advanced phase thus includes also more efficient methods for the radio relays.

2.6.3.8 HetNet

Heterogeneous Network is a general term that does not refer directly to a specific technology or feature as such. Instead, it is a concept related to networks consisting of wide cell coverage areas as well as localized coverage areas, that is, small cells or Home eNodeB elements. Typically, the HetNet concept is deployed in a multi-radio access technology environment. The increasing use of Home eNodeB elements can be foreseen also because they provide reliable and secure mobile broadband services in home and office environments.

HetNet performs best when the automatic interference coordination and handover optimization can be deployed to ensure minimum faults in set-up and operation. Thus, the SON concept is one of the most logical supporting technologies to assist HetNet, and has been extremely useful as long ago as Release 8.

Also other supporting functionalities already also as of Release 8, such as inter-cell interference coordination (ICIC) are useful especially for the radio resource utilization improvements in the cell edge area. Other useful Release 8 functionality includes eNodeB measurements and signaling for inter-cell interference coordination over the *X2* interface. It should be noted that the related eNodeB interference reduction algorithms have been kept by 3GPP as confidential and vendor-specific in order to guarantee a sufficient level of further innovation and competitive environment. It also should be noted that the *X2*-interface is normally not included in Home eNodeB elements, and furthermore, the behavior of the interferences differs from the other macro cell deployment scenarios. One of the clearly notable differences is that the small cells are often deployed and operated by end users, resulting in a lack of awareness of the network operator regarding the essential radio network planning assumptions which in turn may increase the interference levels. This may cause uncontrolled system performance degradation for the eNodeB elements of the network operator (increased dropped call rate, lower data throughput). For this reason, the 3GPP Release 10 defines new ways for the ICIC. The enhancements also are related to the automated maintenance and better error recovery functionality. This is quite an important point as the numbers of small cells increasingly are taking on more roles.

The HetNet concept and other advanced functionalities of LTE-A are discussed in more detail in LTE-A Radio Network in Chapter 5 and Recommendations in Chapter 12.

2.6.3.9 SON

Compared to the previous 3GPP systems, the LTE/LTE-A environment is, both at the same time, simplified with regard to the architecture, and yet more complicated as more processing power is required to handle high data transmission, more small cells, and, in general, a network which will be handling a huge amount of data traffic and signaling. Thus, the role of the Self-Optimizing/Self-Organizing Network (SON) is highly relevant to the set-up, operation and techno-economic optimization.

From the business point of view, SON has the potential to decrease the OPEX drastically. Some of the most essential functionalities are Automatic Neighbor Relation (ANR) and Minimization of Drive Test (MDT), which ease the initial and operational tasks of the operator, for example, via automatic configuration and optimization radio resource management parameters. The technologies for the basis of SON are still being developed, including automated fault management and energy-saving features. The main idea of SON is thus to ensure the highly complex deployment and operational phases can be handled with the minimum risks of faults.

Many of the network deployment and operational phase tasks are common to both UMTS/HSPA and LTE/LTE-Advanced. Thus, the coordinated functionalities of the SON concept over the different RAN solutions offer the most efficient means for OPEX savings.

SON is discussed in more detail in the next few chapters of this book.

2.6.3.10 Other Functionalities

LTE-Advanced has many items already specified in Release 10, such as Local Break Out based on LIPA (Local IP Access) and SIPTO (Selected Internet IP Traffic Offload), which are meant to decrease transport expenses. At the same time, these solutions decrease the latency for distributed services.

The most typical LTE deployment environment contains multiple radio access technologies, including GSM and UMTS/HSPA networks, so the common solutions for 2G/3G and LTE/LTE-Advanced provide a scale of economics for the operators, as well as seamless user experiences for end users [5].

2.6.4 Release 11

Release 11 contains further enhancements for the LTE-Advanced. Some of the relevant items are the following.

2.6.4.1 System Architecture

- Advanced IP interconnection of services (IPXS).
- System improvements to machine-type communications (SIMTC).
- Unstructured Supplementary Service Data (USSD) simulation service in IMS (USSI).
- QoS Control Based on Subscriber Spending Limits (QoS_SSL).
- Optimized Service Charging and Allocation of Resources in IMS while Roaming (OSCAR).
- Inclusion of Media Resource Broker (MRB).
- Non Voice Emergency Services (NOVES).
- Support for 3GPP Voice Inter-working with Enterprise IP-PBX (VINE).

- Anonymous Call Rejection in the CS domain (ACR_CS).
- Support for BroadBand Forum Accesses Inter-working (BBAI).
- SRVCC [39] aspect of eMPS (eMPS_SRVCC).
- Single Radio Video Call Continuity for 3G-CS (vSRVCC).
- Network Provided Location Information for IMS.
- Service Awareness and Privacy Policies (SAPP).
- VPLMN Autonomous CSG Roaming (VCSG).
- Data Identification in ANDSF (DIDA).
- Location-Based Selection of gateways for WLAN (LOBSTER).
- Single Radio Voice Call Continuity from UTRAN/GERAN to E-UTRAN/HSPA (rSRVCC).
- Mobility based on GTP and WLAN access to EPC (SaMOG).
- Roaming Architecture for Voice over IMS with Local Breakout (RAVEL).
- IMS Overload Control (IOC).
- Split TTCN Test Models for IMS testing in TS 34.229-3 (IMS-CCR_Test2).
- Lawful Interception in the 3GPP Rel-11 (LI11).
- EEA3 and EIA3 (new Encryption & Integrity EPS security algorithms).
- Specification of Protection against Unsolicited Communication for IMS (SPUCI).
- H(e)NB security features for UE mobility scenarios (HNB_mob_Sec).
- Generic Bootstrapping Architecture extensions for re-use of SIP Digest credentials (GBA-ext).
- Extensions of Acoustic Test Specifications in TS 26.131 and TS 26.132 (Ext_ATS).
- Enhancements to Multimedia: PSS, MMS, and MBMS Enhancements and (EMM).
- Mobile 3D Video Coding (M3DV).
- IRP framework enhancements to support Management of Converged Networks.
- Management for Carrier Aggregation for LTE.
- IMS Performance Management enhancements.
- Enhanced Management of UE-based network performance measurements.
- CN performance measurements enhancement.
- UTRAN Self-Organizing Networks (SON) management.
- LTE Self-Organizing Networks (SON) coordination management.
- Inter-RAT Energy Saving Management (OAM-IRAT-ESM).
- Release 11 Charging Management small Enhancements.
- Add solutions for Rc – reference point within the Online Charging System CH-Rc).
- Charging for Policy Enhancements for Sponsored Connectivity (PEST-CH).
- Unification of charging session from SIP AS and SRVCC functions in IMS.
- Transit Inter Operator Identifier for IMS Interconnection Charging in multi-operator environment.

2.6.4.2 CT Features

- User Data Convergence – Data Model (UDC_DM).
- Definition of the UICC Application for Hosting Party Module (HPM_UICC).
- Usability improvement of II-NNI specification for inter-connection by means of Option Item list (NNI_OI).
- Enhanced Nodes Restoration for EPC (eNR_EPC).
- Reference Location Information (RLI).

- IMS Stage-3 IETF Protocol Alignment (IMSProtoc5).
- Service Identification for RRC Improvements in GERAN (SIRIG).
- SAE Protocol Development (SAES2).
- GCSMSC and GCR Redundancy for VGCS/VBS (RT_VGCS_Red).
- Support of RFC 6140 in IMS (GINI).
- Enhancements for Multimedia Priority Service – Gateway Control Priority (eMPS_Gateway).
- Inter-IMS Network to Network Interface (II-NNI) enhancements: SIP timers applicability (NNI_timers).
- AT commands for Universal Resource Identifier support (ATURI).
- PS Additional Number (PSAN).
- Generic IMS User Group Over Sh (GenUG_Sh).
- IMS Operator Determined Call Barring (IODB).
- Enhanced T.38 FAX support (MMTel_T.38_FAX).

2.6.4.3 UTRA LTE Features

The following features are:

- extending the 850 MHz Upper Band (814–849 MHz);
- further Self Optimizing Networks (SON) enhancements;
- enhancement of minimization of drive tests for E-UTRAN and UTRAN;
- network energy saving for E-UTRAN;
- E-UTRA medium range and MSR medium range/local area BS class requirements;
- RF Requirements for Multi-Band and Multi-Standard Radio Base Station;
- further enhancements to H(e)NB mobility – Parts 1 and 2.

2.6.4.4 LTE Features

The following features are:

- network-based positioning support for LTE;
- service continuity improvements for MBMS for LTE;
- further enhanced non-CA-based ICIC for LTE;
- new band LTE Downlink FDD, 716–728 MHz;
- LTE RAN enhancements for diverse data applications;
- LTE E850 – Lower Band for Region 2 (non-US);
- LTE for 700 MHz Digital Dividend (LTE_APAC700);
- Relays for LTE (Part 2);
- Signaling and Procedure for Interference Avoidance for in-device coexistence;
- Coordinated Multi-Point Operation for LTE;
- enhanced downlink control channel(s) for LTE-Advanced;
- Public Safety Broadband High Power UE for Band 14 for Region 2;
- improved minimum performance requirements for E-UTRA: Interference Rejection;
- additional special subframe configuration for LTE TDD;
- Rel-11 LTE Carrier Aggregation.

Table 2.8 Options for the location-based services in LTE/LTE-A in Release 11.

Method	UE-based	UE-assisted	eNB-assisted	Release
RF pattern matching	No info available	No info available	No information available	Release 11
UTDOA, uplink	No	No	Yes (eNB measures, LS estimates)	Release 11

2.6.4.5 Others

In addition to the list above, there are plenty of UTRA features enhancement items included in Release 11, such as eight-carrier HSDPA, Uplink Transmit Diversity for HSPA, further enhancements to CELL_FACH, Four Branch MIMO transmission for HSDPA, MIMO with 64-QAM for HSUPA, HSDPA Dual-Band Multi-Carrier combinations. Also GERAN evolves as the Release 11 item list indicates, some of the key items being Full Support of Multi-Operator Core Network by GERAN, and Domain Specific Access Control in GERAN (GDSAC). Some of the system architecture items are studies on IMS-based Peer-to-Peer Content Distribution Services, Non-Voice Emergency Services, Support for 3GPP Voice Interworking with Enterprise IP-PBX, IMS Evolution, Policy solutions and enhancements, IPv6 Migration and SR Voice Call Continuity from UTRAN/GERAN to E-UTRAN/HSPA.

2.6.4.6 eMBMS Enhancements

Since the first MBMS (Multimedia Broadcast Multicast Service) standardization in Release 6, its deployment in practice has not advanced too much. Along with the LTE, as of Release 9, the role of MBMS, or eMBMS (evolved MBMS) might become more important, for example, due to the increasing importance of emergency notification systems. The practical uses are yet to be seen, though.

As can be seen in Table 2.8, the UTDOA and RF pattern matching are part of 3GPP Release 11 while the basis has been created in Release 9.

2.6.5 Release 12

Release 12 again contains enhancements for the LTE-Advanced. Some of the relevant items are the following.

2.6.5.1 System Architecture

- SIPTO Service Continuity of IP Data Session (SIPTO_SC).
- Interworking between MOs using the EPS and Data Application Providers (MOSAP).
- IMS Network-Independent Public User Identities (INIPUI).
- Service and Media Reachability for Users over Restrictive Firewalls (SMURFs).
- Advanced IP Interconnection of Services (IPXS) for national interconnect (IPXSNAT).
- Integration of Single Sign-On (SSO) frameworks with 3GPP networks (SSO_Int).
- Explicit Communication Transfer Blind (ECT Blind) service interactions (ECTB).
- IMS access via Digital Video Broadcast - Return Channel via Satellite (IMSSat).
- Sequential Flexible Alerting (SEQ_FA).
- Language and Modality Information for communications (LangInfo).

- Emergency Session Identification (ESID).
- Prevention of Mobile-Originating signaling and/or data traffic of UE in Connected mode (PMOC).
- LIPA Mobility and SIPTO at the Local Network (LIMONET).
- Operator Policies for IP Interface Selection (OPIIS).
- SMS submit and delivery without MSISDN in IMS (SMSMI).
- IMS-based Telepresence (IMS_TELEP).
- Group Communication System Enablers for LTE (GCSE_LTE).
- Machine-type and other mobile data applications communications enhancements.
- Policy and Charging Control for supporting fixed broadband access networks (P4C).
- IMS Business Trunking for IP-PBX in Static Mode of Operation (BusTI).
- WLAN Network Selection for 3GPP Terminals (WLAN_NS).
- IMS Registration Control (IMS_RegCon).
- User Plane Congestion management (UPCON).
- Proximity-based Services (ProSe).
- Web Real Time Communication Access to IMS (IMS_WebRTC).
- Usage Monitoring Control PCC enhancement (UMONC).
- Application-Based Charging (ABC).
- Enhanced S2a Mobility Over trusted WLAN access to EPC (eSaMOG).
- Optimized Offloading to WLAN in 3GPP-RAT Mobility (WORM).
- Network-provided Location information for IMS Trusted WLAN Access Network case.
- Core Network Overload, User Location Information reporting improvement (CNO ULI).
- Security aspects of Public Warning System (PWS_Sec).
- Security enhancements for usage of GBA from the browser (Web_GBA).
- IMS media plane security extensions (eMEDIASEC).
- Lawful Interception in the 3GPP Rel-12 (LI12).
- Tunneling of UE Services over Restrictive Access Networks (TURAN).
- Specification of the TUAK Algorithm Set (STAS).
- Codec for Enhanced Voice Services (EVS_codec).
- High Efficiency Video Coding (HEVC).
- Mobile stereoscopic 3D services extensions (M3DV_Ext).
- IMS-based Streaming and Download Delivery Enhancements (IMS_SDE).
- Acoustic Requirements and Test methods for IMS-based conversational speech services over LTE.
- MBMS Improvements.
- End-to-End Multimedia Telephony Service for IMS extensions (E2EMTSI).
- Video Coding Enhancements in IMS Messaging and Presence (VCEIMP).
- Enhanced Network Management centralized Coverage and Capacity Optimization.
- Multi-vendor Plug and Play eNB connection to the network.
- Compliance of 3GPP SA5 specifications to the NGMN Top OPE Recommendations.
- Compliance of 3GPP SA5 specifications to the NGMN NGCOR.
- WLAN Management.
- Alarm quality improvements.
- Network Management for 3GPP Inter-working WLAN.
- Energy Efficiency-related Performance Measurements.
- OAM aspects of Network Sharing.
- Short Message Service – Service Center Offline Charging.

- Charging per IP – Connectivity Access Network (IP-CAN) Session.
- Charging using an Alternative Roaming Provider.
- Charging for IMS centralized service (ICS) control.

2.6.5.2 Core Network and Terminal Features

- IMS Emergency PSAP Callback.
- Inter-working between a PLMN with WLAN to access the EPC and a PDN.
- Reporting Enhancements in Warning Message Delivery.
- SRVCC before ringing.
- IMS Stage 3 IETF Protocol Alignment – Phase 6.
- SAE Protocol Development – Phase 3.
- IM-SSF Application Server Service Data Descriptions.
- Diameter-based interface between SGSN and SMS central functions.
- Diameter-based interface between SGSN-GMLC.
- IMS impacts on UICC Application Aspects.
- eMBMS restoration procedures.
- Dual Radio VCC enhancements.
- CT aspects of Signaling of Image Size (Stage 2/3).
- ICS Inter-working Enhancement in MSC-S.
- GPRS Tunneling Protocol for the Control plane Overload Control Mechanisms [40].
- P-CSCF restoration enhancements.
- Support of RTP/RTCP multiplexing (signaling) in IMS.
- Updating IMS to conform to RFC 6665.
- IMS Operator Determined Call Barring enhancements.
- Signaling Improvements for Network Efficiency.

2.6.5.3 UTRA LTE Features

- Verification of radiated multi-antenna reception performance of UEs in LTE/UMTS.
- Further enhancements to H(e)NB mobility – Part 3.
- LTE UE TRP and TRS and UTRA Hand Phantom-related UE TRP and TRS Requirements.
- Support for BeiDou Navigation Satellite System (BDS) for UTRA and LTE.
- BS RF requirements for Active Antenna System.
- New Base Station specification structure.
- L-band for Supplemental Downlink in E-UTRA and UTRA.
- LTE-HRPD (High Rate Packet Data in 3GPP2) inter-RAT SON.
- Increasing the minimum number of carriers for UE monitoring in UTRA and E-UTRA.
- WLAN/3GPP Radio Inter-working.

2.6.5.4 LTE Features

- LTE in the 1670–1675 MHz Band for US.
- LTE in the US Wireless Communications Service (WCS) Band.
- Introduction of LTE 450 MHz band in Brazil.
- Further Downlink MIMO Enhancement for LTE-Advanced.
- Further Enhancements to LTE TDD for DL-UL Interference Management and Traffic Adaptation.

- HetNet Mobility Enhancements for LTE.
- Further enhancements for HeNB mobility-X2-GW.
- 8 Rx Antennas for LTE UL.
- Low cost and enhanced coverage MTC UE for LTE.
- LTE TDD-FDD joint operation.
- LTE Coverage Enhancements.
- Further MBMS operations support for E-UTRAN.
- Dual connectivity for LTE.
- E-UTRA Small cell enhancements - Physical layer aspects.
- Inter-eNB Coordinated Multi-Point (CoMP) for LTE.
- Release 12 LTE Carrier Aggregation.

2.6.5.5 Other Functionalities

In addition to LTE/LTE-A enhancements, the Release 12 work also includes a comprehensive work list for UTRAN and GERAN. Some examples are HSPA signaling enhancements for more efficient resource usage for LCR, HNB Positioning for UTRA, UMTS Mobility enhancements for heterogeneous networks, introduction of ER-GSM band for GSM-R (RT_ERGSM), Downlink Multi Carrier GERAN (DMCG), and New Training Sequence Codes for GERAN (NewToN).

As Release 12 is still being worked on at the time of writing this book, there are plenty of study items included in the standardization. Some highlights of the items are related to Optimized Offloading to WLAN in 3GPP-RAT mobility (FS_WORM), Application Based Charging (FS_ABC), Extended IMS Media Plane Security features, HTML5 for a new presentation layer in 3GPP services (FS_HTML5), management of Heterogeneous Networks, Coordinated Multi-Point (CoMP) operation for LTE with Non-Ideal Backhaul, Positioning enhancements for E-UTRA, and Next-Generation SON for UTRA and LTE. There also are many non-LTE study items like scalable UMTS FDD bandwidth and Scalable UMTS FDD bandwidth by Filtering.

2.6.6 Release 13

At the time of writing this book, Release 13 is still open while Release 12 was frozen in mid-2014. The Release 13 work items will include, for example, RAN Sharing Enhancements (RSE), Service Exposure and Enablement Support (SEES), Service Requirements Maintenance for MTC (SRMMTC), Mission Critical Push To Talk over LTE (MCPTT), and other system architecture items. Furthermore, there will be a Security Assurance Specification for 3GPP network products (SCAS) and LTE-Advanced intra-band contiguous Carrier Aggregation in Band 42, as well as various study items such as Study on Application specific Congestion control for Data Communication (FS_ACDC), Isolated E-UTRAN Operation for Public Safety (FS_IOPS), enhancements for Infrastructure-based data Communication Between Devices (FS_eICBD), need for Multiple Access Point Names (FS_MAPN), Co-ordinated packet data network gateway change for SIPTO (FS_CSIPTO), Flexible Mobile Service Steering (FS_FMSS), Enhanced Calling Information Presentation (FS_ECIP), and Multimedia Broadcast Supplement for PWS (FS_MBSP).

As for the extension of the LTE/LTE-A RF bands, there have been highly active discussions in 3GPP on including unlicensed band support to Release 13, under the title LTE-U (Unlicensed).

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Figure 11.3 LTE/LTE-A Key Performance Indicators.

user impact. As this information can be followed up in real time, an operator is able to respond quickly to the system that is showing deviations compared to the average historical data. The comparison is thus also essential in order to understand if, along with the evolving user base, some critical bottlenecks, for example, in capacity or coverage are forming.

The next step, after the operator has received performance monitoring data reports indicating a potential issue, for example, the new values may differ from the historical values, is to understand the root cause of the change. In many cases, the performance monitoring triggers an alarm for fault management when the issue is serious enough (the normal values are exceeded),

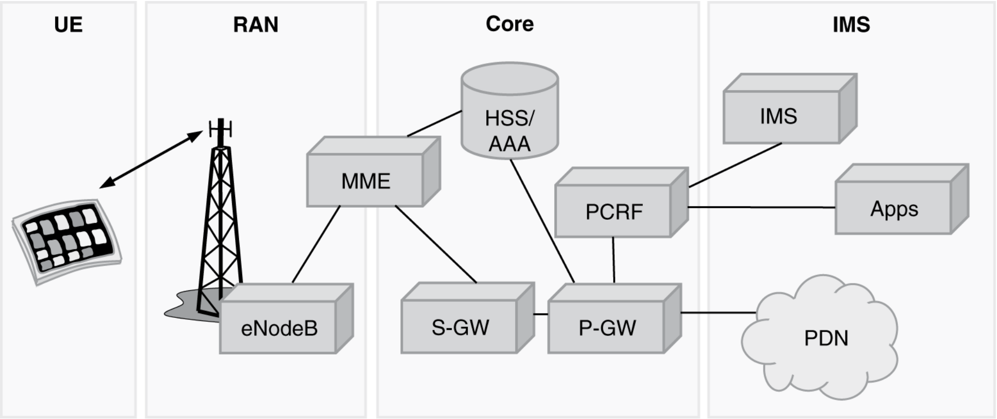


Figure 11.4 Monitoring performance metrics across each layer of the LTE/LTE-A and IMS architecture is important to ensure a high-performing network.

but not always even serious issues can be captured via FM. Thus, the intervention of skillful experts is also needed to understand the often highly complex inter-dependencies of the possible faults and other operator actions (such as a normal network upgrade which may trigger odd alarms and faults).

The following sections clarify items that have key impacts on the performance by high lighting key metrics for the successful monitoring of the LTE/LTE-A network, and present recommended solutions to cope with the challenges of LTE/LTE-A network performance monitoring.

11.2.2 Issues Revealed by PM

11.2.2.1 Authentication

The load caused by authentication creates many issues for carriers. In addition to collecting baselines for internal user metrics, synthetic tests should be used to check the availability of the authentication process (AAA, HLR/HSS) and provide a user experience metric that ensures the UE can be authenticated on the network. Employing a multi-layered testing strategy requires a simple ping on the DNS name (to test the look-up), a port look-up test to query if the port is accessible, as well as a more thorough test of the authentication process itself. This multi layered approach indicates if there is an issue with the server, the process, or the back-end application itself.

11.2.2.2 Firewalls and Load Balancers

The core is front-ended with load balancers and firewalls. Monitoring the number of connections and sessions prevents any overload that might indicate Distributed Denial of Service (DDoS) attacks and ensures the performance of these devices as they protect the core. New load balancers can use the performance information from other parts of the infrastructure to perform on-demand updates to the routes, provide in-line insight, and manage the user function.

11.2.2.3 PDN Gateway and Serving Gateway

In the IP environment, it is important that the PDN Gateway (P-GW) contains sufficient IP address space in the pool to request User Equipment (UE). Alerts due to abnormal allocation, as well as capacity prior to exhaustion, are critical to maintaining user connectivity. Collecting the session and connection history provides a means of understanding baseline usage patterns and triggers an alert due to abnormal behavior.

Understanding the connectivity to the Internet (HTTP requests) allows more efficient routing, and combined with the Serving Gateway (S-GW) QoS metrics and traffic behavior, provides offloading assistance in peering decisions. As the SGW is the connection point for traffic, it is important to make sure that it has sufficient memory and processing power to ensure its serving functions.

11.2.2.4 MME

An important metric for service connectivity is the bearer success history of the end user equipment, as well as its associated ratio of success to failure. Monitoring the S6a interface for an effective success ratio of subscriber information reveals if the UE has successfully entered the network. This data also provides usage information for capacity planning and capital expenditures. In addition, understanding the performance of the transport, including router and switch elements, in the time context with the MME provides an insight as to the impact of the infrastructure on the service.

11.2.2.5 eNodeB

While the eNodeB does not provide direct communication with the UE, it does motivate and manage the complex radio initiatives. It is specifically important to monitor the radio bearer, radio admission, and connection mobility control, as well as the uplink and downlink scheduling. Combining metrics around the radio resource provides a Radio Quality Indicator to allow "hot spot" determination. As the eNodeB provides the forwarding and routing function to traffic transiting the tower, it is important to make sure that the data use to S-GW stays within quality limits.

11.2.2.6 Transport

The performance of all services to and from the UE depends on the devices that transport the packets. Performance monitoring and the creation of thresholds for metrics such as CPU and memory on Layer 1, 2, and 3 devices, as well as the performance metrics (utilization, in/out ratio, level of discards, etc.) of individual interfaces across multiple technologies (Ethernet, MPLS, microwave, etc.) are critical to the delivery of an end-to-end service and each individual service component.

11.2.2.7 Physical IMS Application Servers

The IMS data center is located at the core of the network, containing applications and the hosting servers which are experiencing constant load stress due to the demands of the network. The control mechanisms are not purpose-built hardware, but servers loaded with dedicated software (EMS, authentication, control plane functionality, and IMS core applications). Traditional monitoring of the critical components of these servers is increasingly important along with the deployment of LTE-A, as well as monitoring the processes necessary to keep user sessions active. CPU, memory, processes, and interface statistics provide insight into the health of the devices.

11.2.2.8 Bearer Path Testing

While the performance of devices is important in transit, including metrics for latency, loss, jitter at L3, and frame delay, frame loss, and Frame Delay Variation (FDV) at L2, end-to-end performance is critical to guarantee a good user experience and customer satisfaction. The good performance level of voice and real-time streaming data depends on low latency and loss metrics. In order to ensure the planned quality level, network operations must be alerted in real time to any degradation in performance or increase in latency, jitter, or number of lost packets. While the ITU specifies parameters for synthetic testing (such as jitter < 30 ms), all parameters are changeable and most are likely to be more stringent than the typical industry norm is. Ethernet backhaul emulates the Classes of Service (CoS) inherent within circuit-switched technologies such as ATM and frame relay, in order to meet commitments on bandwidth and QoS. Network engineering and operations must also monitor the performance of their backhaul links and backhaul service providers, easily segment the network and isolate trouble spots, optimize performance, and increase the customer quality of experience.

11.2.2.9 Application Flow

Traffic flows from many different parts of the network can be analyzed for application behavior, along with UE analysis to troubleshoot configuration changes, capacity and traffic engineering. The volume of data from the flow sources is typically too large to be analyzed in real time, but a drill-down into atypical behavior allows a detailed forensic analysis.

11.2.2.10 Signaling

There is a variety of 3GPP signaling interfaces that should be monitored, including S1 for MME to eNodeB communication and X2 for handoff. While it is possible to obtain internal metrics on how many, how fast, and how long, an external metric will provide an additional layer of service for the signaling path. While it was previously mentioned that the bearer path should be tested, it is also good practice to test the signaling path. While it may not be possible to test and measure delay in device to device procedure, it may be possible to test from delay access-device to access device. Monitoring the performance of latency along the signaling path and alerts on threshold violations provide a “first alert” to signaling delays and potential failures. A variety of 3GPP signaling interfaces exist that should be monitored, including S1 for MME to eNB communication and X2 for handoff.

11.2.3 LTE/LTE-A Monitoring Challenges and Solutions

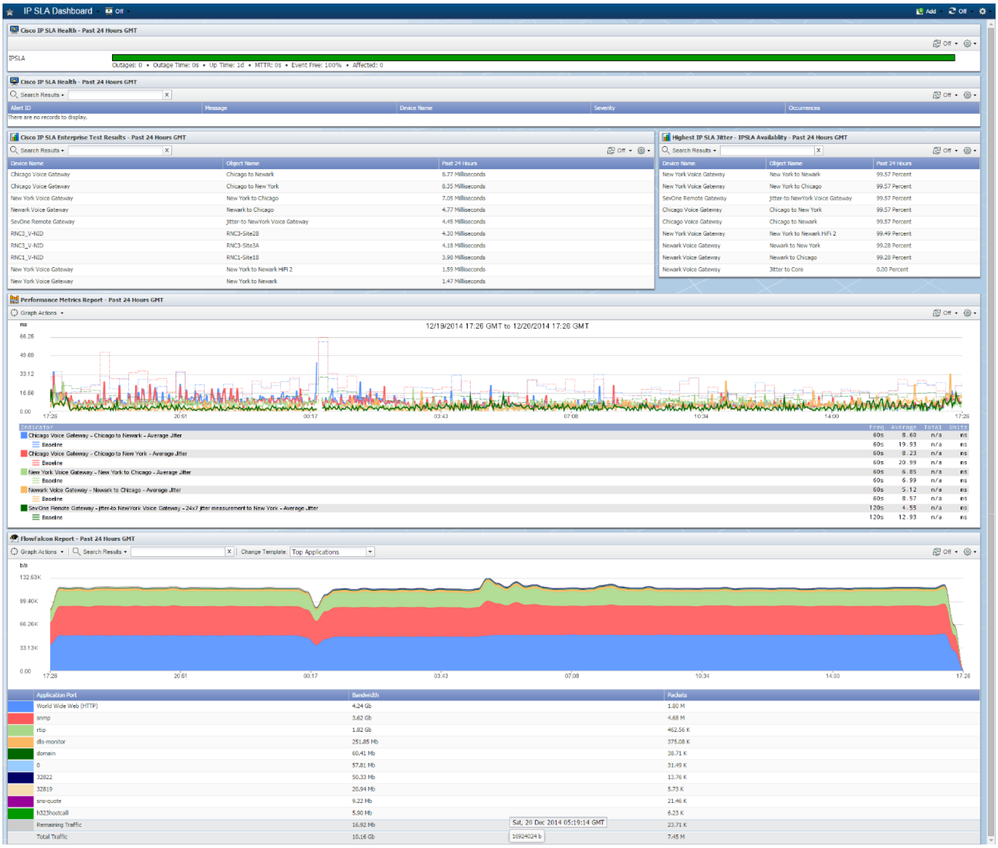
An increase in the number of new technologies offered by major vendors in the LTE market has driven a similar increase in the number of stand-alone management systems that rely on difficult to-access performance data for the specific portion of the network they monitor. SNMP is not always available to the individuals responsible for monitoring the health of specific devices.

Having multiple, disparate performance monitoring and reporting tools for the LTE network presents a number of challenges:

- End-to-end visibility is difficult to achieve from a single pane of glass.
- Correlation of events is problematic.
- Gaps in network visibility increase the service risk.
- Management silos hinder communication among internal groups.
- Troubleshooting becomes more difficult, increasing MTTR.

In addition, these fragmented management tools often do not store historical data for more than four or six weeks, or they do not baseline performance which should be a prerequisite for an intelligent alerting system.

To solve these challenges requires a sufficiently scalable network management and reporting platform. Such a platform ideally should provide an integrated solution with the means to detect performance events and thus minimize their impact on the actual service delivery. One of the examples of commercial products is presented in Figure 11.5 which shows the multiple event monitoring capabilities of SevOne. It is an example of a system which is able to trigger an alert in real time on increased latency, jitter, number of lost packets, and other metrics that impact QoE and foreshadow a degradation of LTE network performance. The benefit of the solution is the visibility of the whole infrastructure of the platform in such a way that single events can be correlated with their impacts on other service components, providing an understanding of the impacts in the end-to-end chain of the network.



Cisco IP SLA Health - Past 24 Hours GMT

IPSLA — Outages: 0 • Outage Time: 0s • Up Time: 1d • MTTR: 0s • Event Free: 100% • Affected: 0

Cisco IP SLA Health - Past 24 Hours GMT

Alert ID	Message	Device Name	Severity	Occurrences

There are no records to display.

Cisco IP SLA Enterprise Test Results - Past 24 Hours GMT

Device Name	Object Name	Past 24 Hours
Chicago Voice Gateway	Chicago to Newark	8.77 Milliseconds
Chicago Voice Gateway	Chicago to New York	8.35 Milliseconds
New York Voice Gateway	New York to Chicago	7.05 Milliseconds
Newark Voice Gateway	Newark to Chicago	4.77 Milliseconds
SevOne Remote Gateway	jitter-to NewYork Voice Gateway	4.45 Milliseconds
RNC3_V-NID	RNC3-Site2B	4.30 Milliseconds
RNC3_V-NID	RNC3-Site3A	4.18 Milliseconds
RNC1_V-NID	RNC1-Site1B	3.98 Milliseconds
New York Voice Gateway	New York to Newark HiFi 2	1.59 Milliseconds
New York Voice Gateway	New York to Newark	1.47 Milliseconds

Highest IP SLA Jitter - IPSLA Availablity - Past 24 Hours GMT

Device Name	Object Name	Past 24 Hours
New York Voice Gateway	New York to Newark	99.57 Percent
New York Voice Gateway	New York to Chicago	99.57 Percent
SevOne Remote Gateway	jitter-to NewYork Voice Gateway	99.57 Percent
Chicago Voice Gateway	Chicago to New York	99.57 Percent
Chicago Voice Gateway	Chicago to Newark	99.57 Percent
New York Voice Gateway	New York to Newark HiFi 2	99.49 Percent
Newark Voice Gateway	Newark to New York	99.28 Percent
Newark Voice Gateway	Newark to Chicago	99.28 Percent
Newark Voice Gateway	Jitter to Core	0.00 Percent

Performance Metrics Report - Past 24 Hours GMT

12/19/2014 17:26 GMT to 12/20/2014 17:26 GMT

Indicator	Freq	Average	Total	Units
🟦 Chicago Voice Gateway - Chicago to Newark - Average Jitter	60s	8.60	n/a	ms
Baseline	60s	19.93	n/a	ms
🟥 Chicago Voice Gateway - Chicago to New York - Average Jitter	60s	8.23	n/a	ms
Baseline	60s	20.99	n/a	ms
🟩 New York Voice Gateway - New York to Chicago - Average Jitter	60s	6.85	n/a	ms
Baseline	60s	6.99	n/a	ms
🟧 Newark Voice Gateway - Newark to Chicago - Average Jitter	60s	5.12	n/a	ms
Baseline	60s	8.57	n/a	ms
🟩 SevOne Remote Gateway - jitter-to NewYork Voice Gateway - 24x7 jitter measurement to New York - Average Jitter	120s	4.55	n/a	ms
Baseline	120s	12.93	n/a	ms

FlowFalcon Report - Past 24 Hours GMT

Change Template: Top Applications

	Application Port	Bandwidth	Packets
🟦	World Wide Web (HTTP)	4.24 Gb	1.80 M
🟥	snmp	3.62 Gb	4.68 M
🟩	rtip	1.82 Gb	462.56 K
🟧	dls-monitor	251.85 Mb	375.08 K
🟩	domain	60.41 Mb	38.71 K
🟦	0	57.81 Mb	31.49 K
🟦	32822	50.33 Mb	13.76 K
🟨	32819	20.94 Mb	5.73 K
🟪	sns-quote	9.22 Mb	21.46 K
🟩	h323hostcall	5.90 Mb	6.23 K
⬜	Remaining Traffic	16.92 Mb	23.71 K
	Total Traffic	10.16 Gb	7.45 M

Sat, 20 Dec 2014 05:19:14 GMT

16924024 b

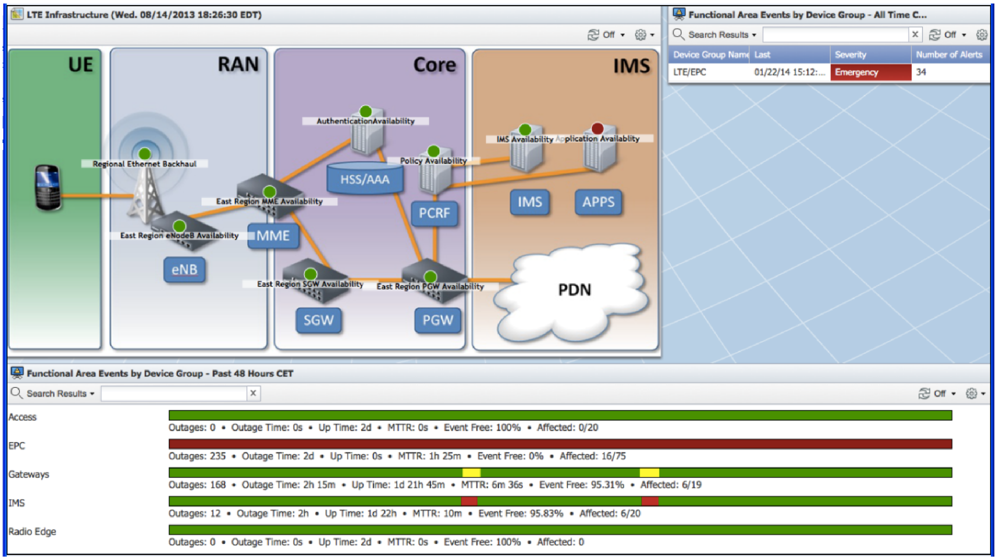
Figure 11.5 PM tools may provide a real-time view of all critical LTE metrics from a single dashboard. Source: Reproduced by courtesy of SevOne.

Following the example of SevOne, the solution provides a collection of metrics from multiple data sources, such as network probes, proprietary business applications and element management systems from network equipment vendors that provide management functions for LTE/LTE-A, IMS and Ethernet backhaul components. Furthermore, the solution is able to present them in side-by-side dashboards, even when SNMP is not available.

The PM system may automatically baseline these statistics as can be seen in Figure 11.6, allowing alerts to be triggered, based on deviations from normal performance. This eliminates false positive alerts, allowing prioritization of service-impacting events and reducing the amount of time to troubleshoot. In addition, the data may be maintained in its raw, non-aggregated form for a pre-defined time period which allows the performing of historical analysis and improved capacity planning. More information on these capabilities can be found in [2].

11.2.4 Performance Monitoring Use Cases

Source [1] lists key use cases essential for 4G LTE/LTE-A monitoring. These cases indicate the usefulness and importance of performance monitoring in order to ensure high quality services to the end users. The essential task of the operator is to make sure that the performance issues are reported and captured in real time in order to take the necessary corrective steps.


LTE Infrastructure (Wed. 08/14/2013 18:26:30 EDT)
Off
UE
RAN
Core
IMS
AuthenticationAvailability
Regional Ethernet Backhaul
Policy Availability
IMS Availability
Application Availablity
HSS/AAA
PCRF
IMS
APPS
East Region MME Availability
East Region eNodeB Availability
MME
eNB
East Region SGW Availability
East Region PGW Availability
PDN
SGW
PGW
Functional Area Events by Device Group - All Time C...
Search Results
Functional Area Events by Device Group - Past 48 Hours CET

Device Group Name	Last	Severity	Number of Alerts
LTE/EPC	01/22/14 15:12:...	Emergency	34

Access
Outages: 0 • Outage Time: 0s • Up Time: 2d • MTTR: 0s • Event Free: 100% • Affected: 0/20

EPC
Outages: 235 • Outage Time: 2d • Up Time: 0s • MTTR: 1h 25m • Event Free: 0% • Affected: 16/75

Gateways
Outages: 168 • Outage Time: 2h 15m • Up Time: 1d 21h 45m • MTTR: 6m 36s • Event Free: 95.31% • Affected: 6/19

IMS
Outages: 12 • Outage Time: 2h • Up Time: 1d 22h • MTTR: 10m • Event Free: 95.83% • Affected: 6/20

Radio Edge
Outages: 0 • Outage Time: 0s • Up Time: 2d • MTTR: 0s • Event Free: 100% • Affected: 0

Figure 11.6 Example of performance monitoring. Source: Reproduced by courtesy of SevOne.

11.2.4.1 Subscription Provisioning Systems

This case study is related to the monitoring of commercially deployed mobile user subscription provisioning systems that authorized new phone activations for the iPhone 5 launch. To ensure the launch was successful, the wireless provider identified the key devices that executed the SIM card activations and partnered with SevOne to build a performance dashboard that showed them all of their data in one place. The dashboard provided visibility on the commercially deployed EMS that is used to help the tracking of SIM card activations for new LTE customers, including full monitoring, baselining and alerting of issues.

The case also contained a SIM OTA service-specific dashboard that monitored activation host performance and session counts, synthetic response time tests from active testing probes, firewalls which front-ended the hosts, and traffic load balancers for the activation hosts. In this case, specific adapters were developed and provided as a part of the EMS of the provisioning system, allowing the customer to be ready for the important marketing campaign.

11.2.4.2 LTE Migration

This case study is related to measuring the level of the network operator's LTE migration. The object and device grouping capabilities of deployed PM system are provided with reports on use and data usage by region and by protocol. This case gives an aggregate view of traffic levels by protocol which shows the comparative traffic levels of LTE, EVDO and HSPA. This data provides insight into the success of different radio access networks' migration efforts as customers are transferred from the legacy networks to the new LTE network. The solution thus shows the level of traffic on LTE, EVDO and HSPA, compared to the total traffic. By segmenting reporting into regions and geographical groups, network operations teams can appropriately assign resources to work on these issues, and provide regional reports to their internal customer business units. Furthermore, by seeing an aggregate value for how much traffic is using each protocol, wireless providers can instantly measure their effectiveness in migrating customers to the network.

11.2.4.3 Router Configuration

This case study is related to the measurements of the ratio between uploads and downloads to identify improper router configurations and possible errors in load balancing. These metrics should stay in the pre-defined range of values knowing that customers typically download two or three times more data compared to uploading. By monitoring the downlink/uplink ratio, it is possible to reliably and quickly identify potential router mismatches and ineffective load balancing designs if the values do not match the planned ones.

A detailed monitoring solution thus provides traffic summary values for download vs. upload traffic volumes, and collects KPIs from the core network devices. Based on this information, the monitoring system may perform math on the collected values using real-time performance monitoring platform to calculate aggregate values. By default, the operator may have a design guideline dictating that these values should stay in a 3:1 ratio; otherwise the mismatch indicates a potential underlying network problem.

Based on this information, network operations teams can quickly identify routing mismatches between the upload and download routes. This visibility helps to avoid service interruptions by performing corrective routing to ensure symmetry in the upload and download paths. This, in turn, results in reduced customer churn and ensures a high end user experience level. Also, customer care teams receive the performance data they need to make sure that users are not affected by improper route configurations or load balancing errors.

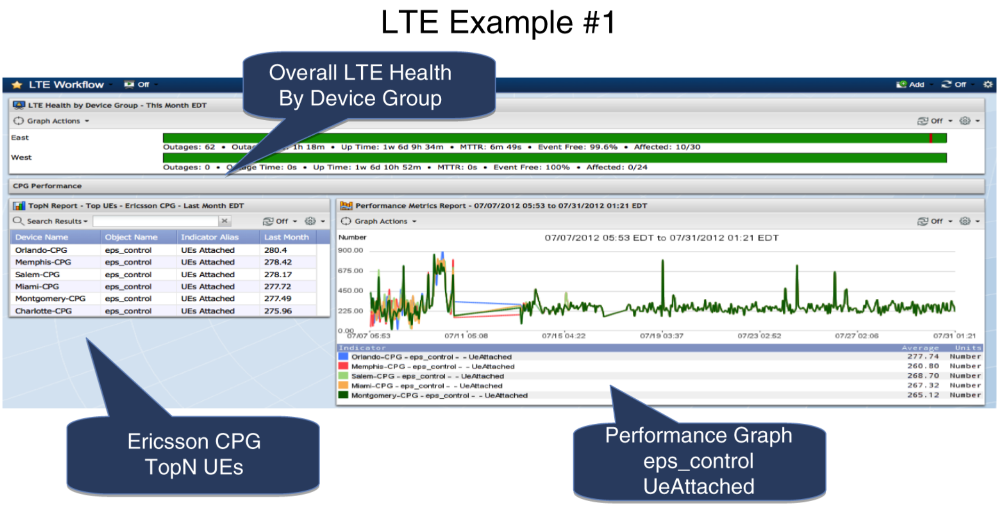
11.2.4.4 Router Functionality

This case study is about monitoring and alerts on temperature data for routers at the cell sites. A well-equipped monitoring system imports and baselines temperature data from the cell sites and warns if temperatures exceed the manufacturer's recommendations. This measure ensures that the packet loss is minimized under harsh weather conditions. Also, remote monitoring of cell sites helps to avoid unnecessary time and expense of truck rolls.

11.2.4.5 Service Monitoring

This case study is about the achievement of service-level monitoring, instead of only by interface-by-interface metrics. As a result, the monitoring system combines separate performance metrics into a single value for monitoring, alerting, and reporting on circuit health or anything else they require. In other words, it allows customers to create a personalized set of KPIs that may not be otherwise available. The solution is able to create reports that reveal data use per market, which gives wireless provider a look into customer trends in regions. Figure 11.7 shows an example of the monitoring display.

After the monitoring and collection of performance results, post-processing of the data is typically needed to interpret the more detailed impact of the network behavior. The measurement data may include, for example, LTE-A error rates, modulation error rates, vector error rates, and other indicators that have an impact on the data throughput and response times. The following sections detail the typical measurements.



LTE Example #1

Overall LTE Health By Device Group

Ericsson CPG TopN UEs

Performance Graph eps_control UeAttached

LTE Workflow

LTE Health by Device Group - This Month EDT

East	Outages: 62 • Outag 1h 18m • Up Time: 1w 6d 9h 34m • MTTR: 6m 49s • Event Free: 99.6% • Affected: 10/30
West	Outages: 0 • O age Time: 0s • Up Time: 1w 6d 10h 52m • MTTR: 0s • Event Free: 100% • Affected: 0/24

CPG Performance

TopN Report - Top UEs - Ericsson CPG - Last Month EDT

Device Name	Object Name	Indicator Alias	Last Month
Orlando-CPG	eps_control	UEs Attached	280.4
Memphis-CPG	eps_control	UEs Attached	278.42
Salem-CPG	eps_control	UEs Attached	278.17
Miami-CPG	eps_control	UEs Attached	277.72
Montgomery-CPG	eps_control	UEs Attached	277.49
Charlotte-CPG	eps_control	UEs Attached	275.96

Performance Metrics Report - 07/07/2012 05:53 to 07/31/2012 01:21 EDT

07/07/2012 05:53 EDT to 07/31/2012 01:21 EDT

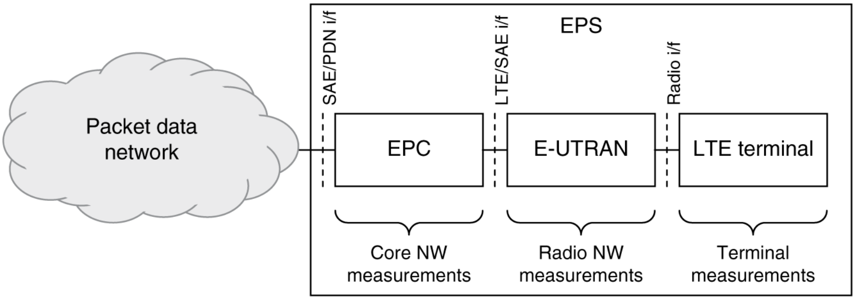
Indicator	Average	Units
🟦 Orlando-CPG - eps_control - - UeAttached	277.74	Number
🟥 Memphis-CPG - eps_control - - UeAttached	260.80	Number
🟩 Salem-CPG - eps_control - - UeAttached	268.70	Number
🟧 Miami-CPG - eps_control - - UeAttached	267.32	Number
🟩 Montgomery-CPG - eps_control - - UeAttached	265.12	Number

Off
Add
Off
Graph Actions
Off
Search Results
Off
Graph Actions
Off
Number
900.00
675.00
450.00
225.00
0.00
07/07 05:53
07/11 05:08
07/15 04:22
07/19 03:37
07/23 02:52
07/27 02:06
07/31 01:21

Figure 11.7 Example of the PM. Reproduced from [1], with permission from SevOne.

11.3 Measurement Methodology

The LTE/SAE measurements are needed both in the core (EPC) and radio (LTE/LTE-A) parts of the evolved packet system as shown in Figure 11.8. Also LTE terminals require special attention especially in the development phase of the equipment. Not only the field and network measurements are essential, but the operational phase of the LTE/SAE network regularly requires performance revisions. These can be done with field test equipment as well as by using the new LTE/SAE specific network statistics measurements directly from the network elements. The network equipment providers tend to add these measurements for basically all of the needed statistic types, including the call drop rate, the blocking rate, and the radio resource error rate. Furthermore, the key performance indicators are an essential part of the performance monitoring of the networks, with the possibility of creating operator specific formulas for special measurements.



Packet data network
SAE/PDN i/f
LTE/SAE i/f
EPS
Radio i/f
EPC
E-UTRAN
LTE terminal
Core NW measurements
Radio NW measurements
Terminal measurements

Figure 11.8 The main reference points for the interface measurements between the core network, the radio network and the air interface.

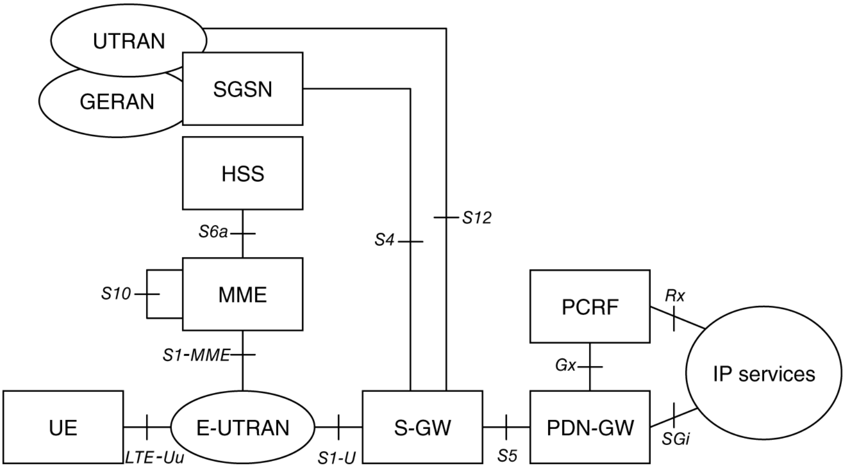


Figure 11.9 The LTE/SAE interface measurement points.

11.3.1 Measurement Points

The possible measurement points of LTE/SAE can be seen in Figure 11.9.

11.3.2 Principles of Radio Interface Measurements

The radio interface measurements are essential in the deployment and operational phases of the LTE/LTE-A network. The following sections describe the special characteristics of LTE/LTE A and the new aspects in the measurements.

The LTE/LTE-A radio interface is based on OFDM (Orthogonal Frequency Division Multiplexing) in the downlink, and on the SC-FDMA (Single-Carrier, Frequency Division Multiple Access) in the uplink. This solution provides a scalable bandwidth selection between 1.4–20 MHz. In addition, LTE/LTE-A supports both FDD (Frequency Division Duplex) and TDD (Time Division Duplex) modes.

Figure 11.10 shows the principle of the LTE/LTE-A downlink transmission in the time domain. Each resource element corresponds to a single OFDM sub-carrier over a period of one OFDM symbol. The channel separation of downlink is defined as 15 kHz in the normal mode of the transmission. In addition, the broadcast mode of LTE can use a 7.5 kHz raster size. In the uplink, LTE uses SC-FDMA with a scalable band.

Because Release 8/9 LTE functions within a maximum of 20 MHz bandwidth – which is four times larger than previously has been the case in the UMTS system – it creates special requirements for the measurement equipment. Furthermore, the carrier aggregation (CA) of LTE-A allows the combination of a maximum of five carriers, providing a maximum of $5 \times 20\,\text{MHz} = 100\,\text{MHz}$ band for high-speed data transmission. The HW and SW of the measurement equipment should thus be able to interpret all the received radio parameters and their values, as well as the performance figures of the measured connection. The latter includes, for example, the data transmission speed (Mb/s), the latency of the data transmission (s), the jitter, that is, the variations of the latency, bit error rate (%), modulation error rate (%) and frame error rate (%).

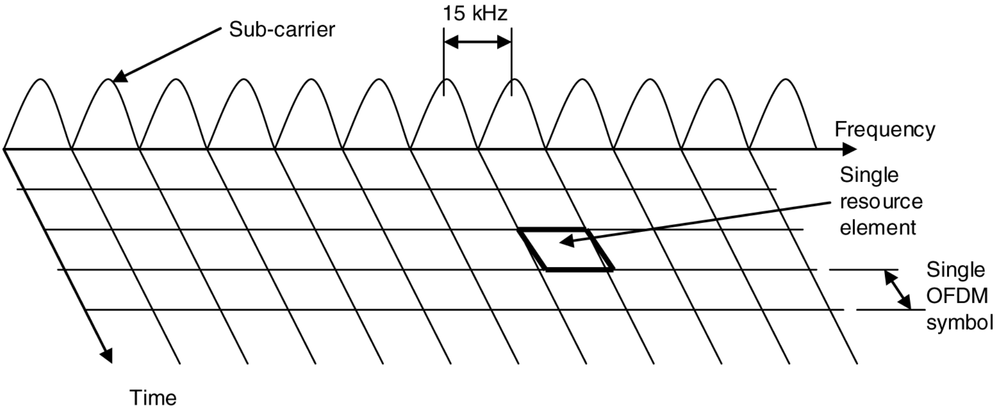


Figure 11.10 The principle of the OFDM downlink.

The measurement needs of the LTE depend naturally on the development phase of the network. In the initial phase of the system, when the equipment (network elements or user equipment) is not yet necessarily available partially or completely, th LTE simulator is a very useful tool for estimating the network performance under the planned circumstances. It can be used to produce performance figures for different traffic scenarios and user profiles, including the combination of different profiles with the varying uplink and downlink data transmission of different applications as FTP upload and download, web browsing, VoIP traffic with varying codec qualities and e-mail traffic. In this way, the functionality and performance can be estimated in advance under normal and stressed conditions, to make sure the selected capacity and other technical characteristics of the network comply with the estimated traffic.

Also the coverage areas as a function of the capacity and quality can be estimated. One of the most useful criteria is the bit error rate as a function of the radio channel type that can be varied between the line-of-sight types of AWGN (Additional White Gaussian Noise) to a highly multi-propagated environment in the dense city center that produces Rayleigh fading as shown in Figure 11.11. The well-equipped simulator environment should also include other propagation scenarios, including all the ones mentioned in 3GPP measurement specifications, and preferably also additional ones with the possibility of setting up personalized propagation environments. The error margin of the estimated performance depends on the accuracy of the simulator's channel models, which can be enhanced via the practical measurements.

In the beginning of the system introduction, in the early phase of the element production, a base station tester is a typical example of the equipment that is needed in the type approval processes. Equally importantly the type approval has to be carried out for the new terminal types. The quality of both hardware and software of the radio equipment needs to be measured in order to avoid problems in the early deployment of the networks. The tester equipment can be integrated into the complete measurement centers that include a large set of tool libraries for the development and execution of the test cases. The tester package typically includes signal generators and RF test equipment meant for laboratory conditions.

The measurement equipment can be modular, that includes a tester platform for LTE and other mobile technologies, in order to ensure common interworking of the equipment of different systems in accordance with the standard's definitions. This type of measurement

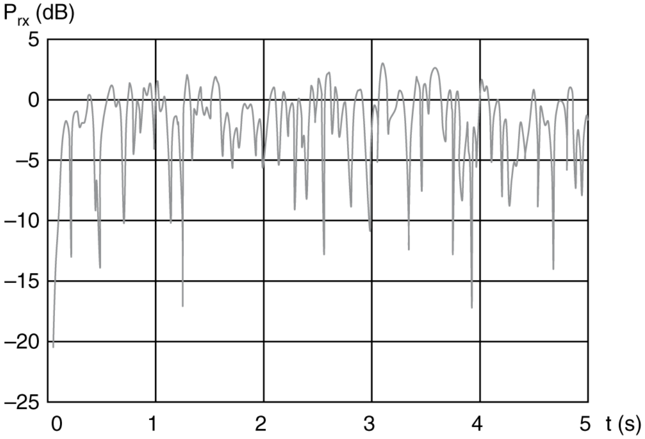


Figure 11.11 An example of the measurement of the received power level when the Rayleigh fading is present.

center may include third party measurement equipment that is integrated into a common control center that takes care of the management of the separate parts of the measurements. This type of solution is useful especially in the terminal testing and pre-type approval testing.

In the implementation phase of the LTE/LTE-A, it is still possible to use, for example, LTE signal generators and signal analyzers. Both the LTE/LTE-A network and terminal inter operability testing (IoT) between different equipment vendors can be carried out in laboratory conditions by using the signal generators or in the more realistic environment in the indoor and outdoor test networks by using commercial or pre-commercial terminals.

In the initial phase of new technology such as LTE, it can be assumed that differences will appear in the functionalities of the various solutions of different equipment vendors. This is due to the fact that the LTE standards are highly complicated and that it is challenging to create test specifications and requirements that will cover all the essential functionalities of the system. In the case of problems with interworking, one of the most useful tools is a protocol analyzer. It displays and stores the signaling flow in the desired level between the network elements. The analysis can be done in real time or by playing the measurement results in the display of the same analyzer. Also the post-processing can be performed based on the stored measurements, either with the same equipment or with separate, more specific, post-processing and analyzer tools.

When the LTE/LTE-A eNodeB infrastructure is about to be integrated and commissioned, the coverage area measurements can be executed with field test equipment. The RF analyzer is one of the most logical selections in the early phase, but as the networks develop, it is logical to carry out the measurements with vehicle-mounted outdoor receivers, or with portable testers indoors and other locations that are difficult to access by car. The test equipment may contain a common platform for data collection, display and pre-analysis, whereas the actual radio measurements are done using commercial LTE terminals and/or third party scanners.

11.3.3 LTE-A Measurement Devices

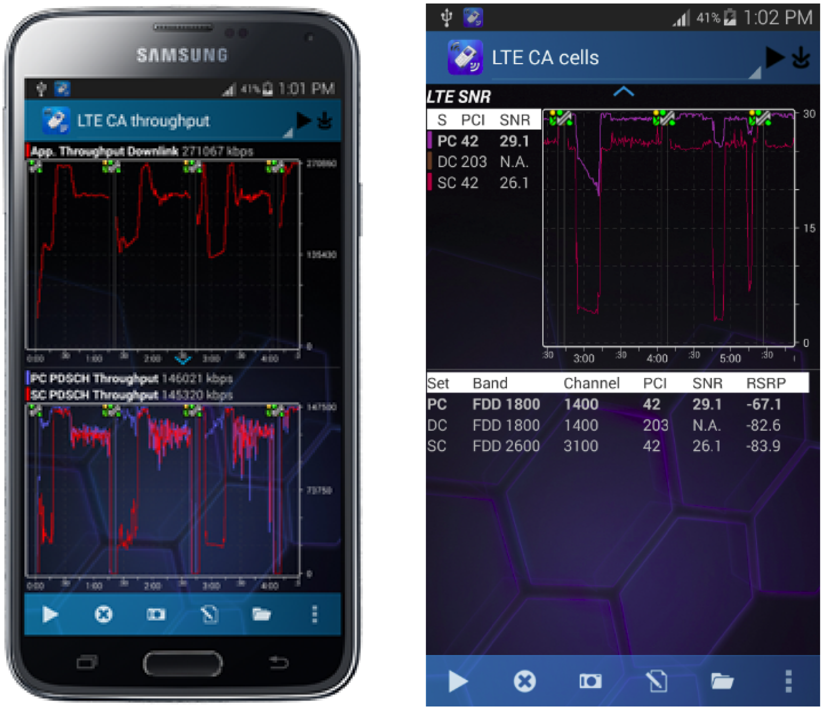
The easiest way to execute often sufficiently detailed LTE/LTE-A radio measurements is by using an LTE handset that is equipped with the capabilities to measure and store the criteria of interest, like received power levels, signal quality and other available parameter values that are transferred between the UE and the eNodeB.

Examples of such currently available equipment are Anite's Nemo Outdoor and Invex systems, and applications running directly on a terminal, that is, Nemo Handy-A 2.40 and Nemo Walker Air 1.30 that support LTE-A Carrier Aggregation (CA) and device category 6 [3]. In order to take into account the typical application use of end users, these devices also can test the performance of the system with applications like YouTube, Dropbox and social media.

One of the essential functionalities of LTE-A is CA which needs to be tested in a practical manner by operators deploying the functionality in the network. Nemo Handy LTE-A is able to measure the performance of the CA with a Category 6 device mode which is able to provide data rates up to 300 Mb/s via 2 × 20 MHz aggregated bandwidth.

The assurance of the correct functioning of advanced CA takes place typically via trialing and piloting, and properly prepared test equipment is essential in this phase. The benefit of a handheld measurement device is the ease of carrying it to locations where larger equipment is not able to access, as in many indoor locations. In order to complement the methodology in the longer term, the set-up can include a portable benchmarking solution, Walker Air, which contains support for the LTE-A terminal Samsung Galaxy S5 G901F and offers the same benefits as Nemo Handy-A.

Figure 11.12 presents the idea of the portable device and display of the set-up for multiple simultaneous phones. In the results window on the left-hand side of Figure 11.12, the


SAMSUNG
41% 1:01 PM
LTE CA throughput
App. Throughput Downlink 271067 kbps
270860
135430
0
0:00
1:00
2:00
3:00
4:00
PC PDSCH Throughput 146021 kbps
SC PDSCH Throughput 145320 kbps
147500
73750
0
41% 1:02 PM
LTE CA cells
LTE SNR
30
15
0
:30
3:00
4:00
5:00

S	PCI	SNR
PC	42	29.1
DC	203	N.A.
SC	42	26.1

Set	Band	Channel	PCI	SNR	RSRP
PC	FDD 1800	1400	42	29.1	-67.1
DC	FDD 1800	1400	203	N.A.	-82.6
SC	FDD 2600	3100	42	26.1	-83.9

Figure 11.12 Nemo Handy-A and Walker Air are examples of handheld LTE-A RF measurement equipment. Source: Photo reproduced with permission from Anite © 2015.

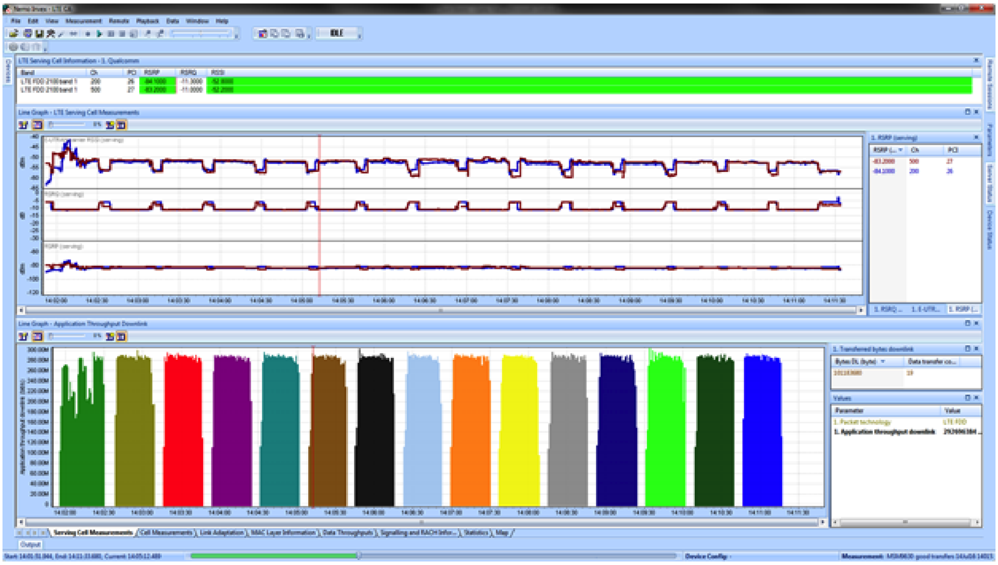


Figure 11.13 Examples of CA KPIs.

composite application layer throughput is shown that displays the PDSCH throughput values in the graph in lower section of the display. The right-hand side of Figure 11.12 shows carrier components, their levels and quality.

The most detailed and accurate field measurements require a more complete set of functionalities than handheld devices are able to provide. The benefit of the handheld device is the ease of carrying it in practically all the locations where the end users are, and the results reflect the realistic RF performance via the same use as the users practice (including body/hand attenuation), more in-depth results and real-time analysis can be achieved via the more advanced set-up using the Nemo Outdoor test tool with more flexible graphing, signaling and IP capture capabilities [4].

One of the references in the mobile communications industry, Nemo Outdoor equipment also supports CA and Category 6 devices. This is a laptop-based wireless network drive test solution which supports over 270 terminals and scanning receivers of major network technologies. It is designed for testing, trialing and for commercial phases to measure CA and Category 6 devices with 2 × 20 MHz DL bandwidth. Examples of carrier aggregation KPI are shown in Figure 11.13.

For LTE/LTE-A peak throughput measurements and monitoring, it is important to select useful coverage location with good quality LTE signal and adequate test server in place. For this measurement type, SINR has to be very good. An example of such measurement conditions is shown in Figure 11.13. Another key item for LTE-A performance measurement is to ensure that the respective server is located in the network with guaranteed, high speed connections so that the set-up is able to enable LTE-A peak throughput.

11.3.4 LTE Traffic Simulators

For the EPC, protocol analyzers are useful in the network optimization as well as in fault management. Nevertheless, if no functional network is not yet available, or the planned

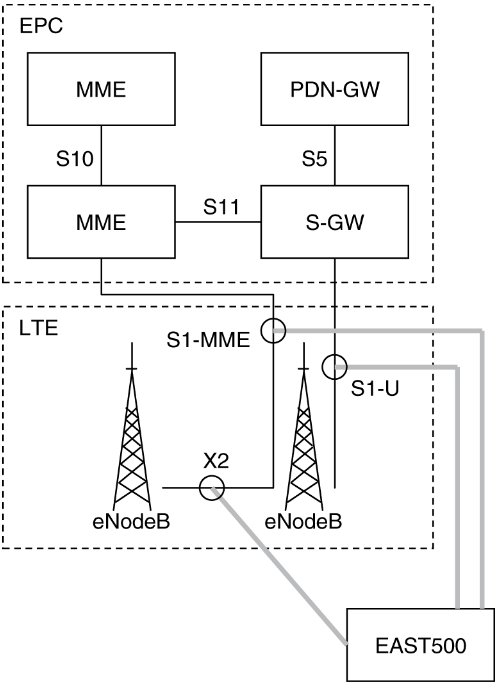


Figure 11.14 The reference measurement points of LTE load simulations.

features require further investigation without yet introducing them to the live environment due to potential faults, the performance and functionality of the complicated scenarios can be investigated via simulators. LTE, and especially fully equipped LTE-A generate considerably more signaling and traffic load compared to the previous mobile networks. It is logical to include separate high-performance servers in these cases for the creation of the realistic loads in large areas.

One example of this type of equipment for the LTE performance evaluation is the NetHawk (EXFO), which has together with Aeroflex developed an integrated test system EAST500 [5]. The system includes simulator, measurement and analyzer blocks, which can be used for LTE performance on a large scale before commercial traffic is available. The packet contains the radio interface measurement module by Aeroflex and the application tester of NetHawk. The outcome of the investigations gives a realistic estimate about eNodeB performance and capacity behavior in the realistic field conditions and traffic profiles of the users. Because eNodeB contains considerably more functionalities compared to UMTS/HSPA NodeB, the measurements and simulation equipment must be updated to support the higher data rates and heavier signaling loads. The data traffic could be estimated to be around ten times more in a typical scenario, which increases the requirements of the analysis accordingly. The equipment thus contains updated IT elements like servers in order to handle the simulated traffic.

Figure 11.14 shows the typical network reference points that can be investigated with EAST 500 equipment. The equipment can also be used to simulate the user data transmission layer as well as the signaling traffic load via the realistic terminal emulation. As the equipment supports all the defined LTE/LTE-A protocol layers, it can be used for the functional testing of eNodeB performance by varying load, and with different bit error rates experienced by the users.

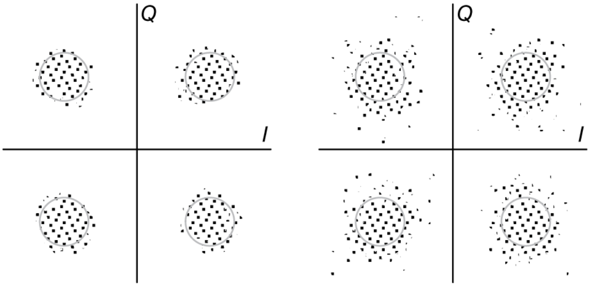


Figure 11.15 The principle of MER measurement results. The first diagram indicates acceptable MER level whereas the second diagram shows potential issues due to the wider variation of the received constellation points.

In a case of urgency, one feasible solution is to perform LTE/LTE-A measurements by upgrading the SW of earlier test equipment, if this option is supported by the test equipment vendor. Some examples of such earlier equipment type that will have the necessary LTE/LTE A capabilities are the vector analyzer, signal generator, signal emulator and signal analyzer. The updated SW includes the LTE/LTE-A capabilities both in the uplink and the downlink with the respective 3GPP test specification definitions. This upgraded equipment can be used to measure the eNodeB and terminal, for example, in the type approval tests, combined with the baseband signal generator, channel emulator and vector signal emulator. The functionality can also include the automatic DCI channel coding, channel definitions, power setting and scheduling as well as the access of the terminal to the network.

11.3.5 Typical LTE Measurements

LTE measurements typically need to be executed in both the uplink and the downlink directions. Typical measurement cases are related to the frequency error, transmitted power level, modulation error rate (MER) and error vector magnitude (EVM). MER indicates the accuracy of the modulation, which can be interpreted from the I/Q-diagram as shown in Figure 11.15.

The EVM value indicates the performance of the demodulator in the noisy environments in a slightly different way. The measurement equipment needs to note the position of the symbol obtained from the carrier wave in the output of the demodulator. This result is compared with the theoretical location of the symbol in I/Q-axis, and the occurred error in the position is shown in percentage scale. Figure 11.16 clarifies the idea of the EVM. The measurements are carried out typically on all of the subcarriers within the selected segment. If the averaging of the results is selected, also the maximum and minimum values can be displayed.

EVM is closely related to the modulation error rate. In practice, it indicates the signal-to noise ratio of the digitally modulated signal in dB.

Another measurement case is related to the constancy of the spectrum and indicates the amplitude, difference in the amplitudes, as well as phase and group delay for each subcarrier. This measurement is useful for solving OFDM-specific issues, like inter-symbol errors.

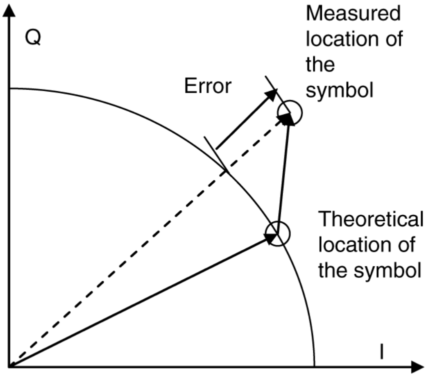

Q
Measured location of the symbol
Error
Theoretical location of the symbol
I

Figure 11.16 The principle of the Error Vector Magnitude (EVM).

The EVM as a function of the subcarrier graphically shows the vector errors for each subcarrier for a certain symbol or a group of symbols. The measurement result can be displayed at the same time for the mean values (RMS) and peak values, which provides the momentary vector error measurements. The EVM as a function of symbols graphically shows the vector error ratio for each symbol either for a part or for the whole set of subcarriers.

CQI (channel quality information) is one of the most important LTE measurement items. It is derived from the HSPA definitions, and it indicates the channel quality in a single value by combining different quality-related items.

Other useful LTE measurements are also the channel's received power level, the use level of the band, the leak power of the neighboring channel and the mask of the spectrum source.

A downlink-specific LTE measurement set can include the power vs. resource block which shows the power level of each resource block over a single subframe or over a larger set of sub-frames. The impact of the power increase for each resource block can thus be visualized by observing the power distributions. It is also possible to simultaneously observe a set of constellation diagrams, which eases in the fault resolutions. In the uplink direction, the time-based EVM measurement is shown individually for each symbol.

As an example, let's investigate the Rohde & Schwarz R&S FSQ-K100 measurement equipment. It can display the following downlink and/or uplink LTE measurement results:

- Power level as a function of time (DL, UL).
- EVM as a function of the carrier (DL).
- EVM as a function of the symbol (DL, UL).
- Frequency error as a function of the symbol (DL).
- EVM as a function of the sub-frame.
- The flatness of the spectrum (DL, UL).
- The group delay of the spectrum (DL, UL).
- The difference of the flatness of the spectrum (DL, UL).
- Constellation diagram (DL, UL).
- Statistics on the CCDF and allocations.
- EVM per timeslot (DL).
- Statistics on CCDF (DL, UL), allocations (DL, UL) and signal flow (DL).

11.3.6 Key Performance Indicators

The Key Performance Indicator (KPI) refers to a measurement item that is essential to understanding the realistic quality of the radio and core network. In other words, the KPI represents specific traffic characteristics that indicate the required minimum performance of a specific traffic profile. KPIs thus reveal if a device or equipment meets the agreed reliability criteria in order to be deployed. Due to the advanced technology and technical performance of LTE and LTE-A, they include new KPIs that are useful in a parallel fashion with the “traditional” indicators.

The complete process of network quality investigation contains the collection of the KPIs, as well as the analysis and evaluation of the values. For the collection, both Performance Monitoring (PM) and field testing can be performed.

The PM is capable of collecting and storing a vast amount of network performance values, such as received power level and quality indicators, dropped and successful calls, and call break codes that aim to reveal the reason for the issue. Many of the single values that the network provides are useful as such for investigating the quality of the network. These values include Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), cell aggregate data throughput in downlink and uplink, and cell edge throughput per user in downlink and uplink. As a rule of thumb, the downlink direction is more significant than the uplink for understanding the network performance, so typically it is sufficient to include the downlink variants in the most important KPI set.

The RSRP indicates the Reference Signal level, and is defined as the linear average that takes into account the resource element power contributions for those ones that carry cell-specific reference signals. RSRQ indicates the reference signal quality in such a way that it is the ratio of:

$$RSRQ = \frac{N \cdot RSRP}{RSSI_{LTE}},$$

where $RSSI_{LTE}$ refers to the E-UTRA carrier RSSI (Received Signal Strength Indicator) while N is the number of RBs of the E-UTRA carrier RSSI bandwidth under measurement. The RSSI is obtained by calculating the linear average of the total received power level observed in OFDM symbols that contain reference symbols for antenna port 0. Furthermore, this KPI depends, for example, on the bandwidth, N resource blocks of UE from all sources including serving and non-serving cells nearby, and adjacent channel interference. As the value depends on the load level, the acceptable RSRQ value may be set, for example, to -15% for 50% cell load, and -18 dB for 100% cell load in the network dimensioning.

The actual dimensioning of the network, or the criteria that complies with the planned level, can be designed in such a way that, for example, RSRP needs to be -98 dBm for 10 MHz bandwidth at 700 MHz LTE band. Furthermore, the compliance of this value needs to be designed, for example, in such a way that the value needs to be met in at least 95% of the geographical locations of the cell. These values are operator dependent and the most concrete means for differentiating in a competitive environment as they indicate the level of coverage and quality.

The cell’s aggregate data throughput refers to the sum of the throughput values of all the active users under the cell with a certain bandwidth, at a given time. Various features contribute to the achievable value, such as carrier aggregation, device category, and so on. The value can be estimated via simulations. In the network dimensioning, the throughput value should be achieved at a given percentage of the locations.

The cell edge user data throughput in the downlink follows the same principles, including the effect of the bandwidth, but the data value in this region is the lowest achievable. The dimensioning value could be decided by, for example, taking the case of 50% of the users that should achieve at least the planned value per user.

These single values can be further analyzed by the PM or via post-processing in such a way that the performance can further be understood and compared in a practical manner. As an example, if the dropped calls due to the lack of coverage D_{outage} and the total number of call attempts $C_{attempts}$ are known as single values over the selected time t, then the percentage of the dropped call rate due to the outage is straightforward to calculate by:

$$D_{rate\_outage} = 100 \cdot \frac{D_{outage}}{C_{attempts}}. \tag{11.1}$$

This formula pre-sets a typical example of the KPIs that the PM may contain, either by default set by the network element manufacturer or in a personalized way by operator. The KPI values are typically stored over the long term in order to provide means for comparing the results. Via the PM analysis or post-processing of the raw data, it is thus possible to observe numerous cases, like the increasing number of dropped calls on weekdays, or seek systematic patterns in network use. One example of the benefits of understanding the capacity and quality behavior as a function of time, location, region, annual seasons, and so on is that if the pattern is repetitive, it is possible, for example, to provide temporary capacity. A classic example is some seasonal major event in a football stadium which can be handled by concentrating more network resources in that area via SON functionality, or by providing physical, additional eNodeB elements with high-speed connectivity to the core network. Many KPIs are presented in the publicly available material, for example, in [6]. The general division of KPIs for LTE network services can be categorized as follows:

- Application services.
- LTE end-to-end network service.
- E-RAB and RB radio bearer services.
- X2, S1, S5/8 and external transport bearer services
- LTE network elements.

Figure 11.17 summarizes these KPIs in the LTE/LTE-A/SAE architecture as interpreted from the requirements of 3GPP TS 32.451 [7] and definitions of the KPIs [8]. Based on these references, the following KPIs are defined: accessibility, retainability, integrity, availability, and mobility.

There also are KPIs for LTE applications which are service-specific. The relevant applications to consider for KPIs are, for example, web browsing, data download and upload, audio and video streaming, and VoIP service.

Some of the relevant wireless backhaul KPIs that directly influence the performance of backhaul networks may be collected in the following list as presented in [9].

- Frame delay, or latency, refers to the time difference from the moment when the frame (or packet) initiates from the originating port and the time when it arrives at the destination port. Frame delay has an impact on the quality of real-time data, such as voice calls and video transmission.

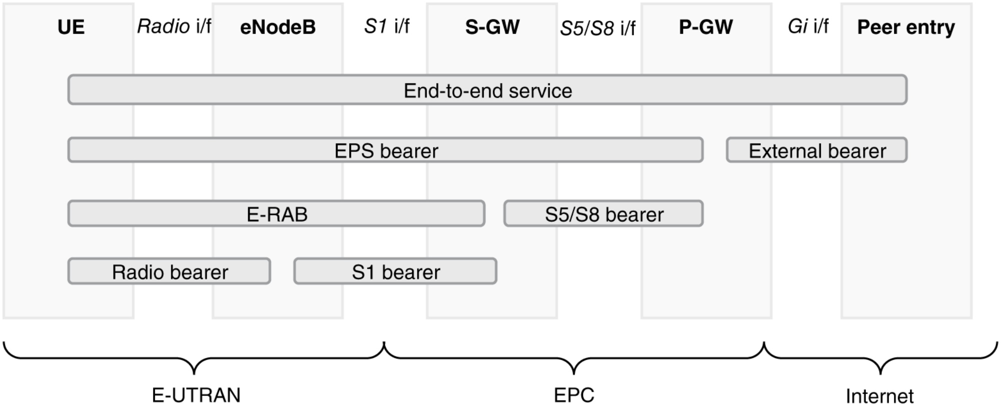


Figure 11.17 The position of LTE/LTE-A/SAE KPIs.

- Frame loss has an important impact on real-time services such as voice and video calls, synchronization and management of control traffic. Frame loss results in the user's poor quality experience. In addition, the control packet loss increases latency and connectivity failures.
- Bandwidth dictates the maximum bit rate.
- Frame delay variation, that is, jitter, is seen as the difference in the arrival times of different data packets. Jitter is the result of network queueing the data and differences in the bursts sent to the following hop. There also may occur random prioritization in the transmission which further contributes to jitter. In the worst case, the large variations in jitter may have a negative impact on the receiver's buffers which leads to their over-use or under-use. In general, real-time applications are especially vulnerable to jitter. If the buffers cannot handle (stabilize) the jitter, this results in poor Quality of Experience (QoE) due to packet loss.

Table 11.1 summarizes the impacts of these KPIs as interpreted by [9]. One of the ways to measure these is based on ITU-T Y.1564 [10] which refers to the standard measurement of the performance of Ethernet-based services over point-to-point or point-to-multipoint networks.

11.3.7 Type Approval Measurements

The 3GPP technical specification 36.214 [11] describes the measurement definitions of the radio interface of E-UTRAN terminals and network, with the terminal being either in idle or connected mode. The most important examples are the following.

Table 11.1 Estimation of the importance of the impact of KPIs. 0 means no sensitiveness, whilst "+" refers to sensitive and "++" to very sensitive.

KPI	Data	Real-Time Data	High Priority Data
Bandwidth	++	+	+
Frame loss	++	++	++
Frame delay	+	+	+
Frame delay variation	0	++	0

Reference Signal Received Power RSRP is calculated as the linear average (in absolute power levels) of those resource elements that are transporting cell-specific information. If reception diversity is activated, the received power level is calculated by averaging the power levels of the separate reception paths.

Reference Signal Received Quality (RSRQ) is defined as a ratio of the power level of the resource blocks (RB) and the signal strength of the signal strength of the whole E-UTRA carrier, which is called the Carrier Received Signal Strength Indicator.

Other measurements are, for example, the received code power level of UTRA FDD mode, the received chip-based energy divided by the power density of the band (Ec/No), RSSI and code power of the UTRA TDD mode, downlink power level of the E-UTRA, the received interference power level, and the thermal noise power level.

The basic measurements of LTE radio interface are related to the quality of the signals in both uplink and downlink. These measurements include MIMO analysis when applicable. In the basic measurements, the measurement equipment should support all the cases with the bandwidth of a single carrier up to 20 MHz. In the case of a multi-carrier, up to five carriers need to be supported in fully equipped LTE-A. Also all the modulation types should be found in the basic set of measurements, that is, QPSK, 16-QAM and 64-QAM, as defined in the 3GPP specification 36 series. The OFDM basic investigations can be related to the quality of the modulation (e.g., Modulation Error Rate, MER) as well as to the other OFDM functionalities such as the size of the transport block, the allocation of the resource block, different protection cycle sizes (CRC) and their combinations.

The quality of the modulation of the transmitter can be investigated at a detailed level, for example, by measuring the EVM value per OFDM carrier, symbol, timeslot and resource block.

11.3.8 Modulation Error Measurements

The interferences and non-optimal radio conditions in the fast varying signal levels due to, for example, multipath propagation or inter-symbol interferences, can change the positions of the occurred samples in the I/Q constellation diagram. Figure 11.18 shows two examples of the erroneous reception. The first shows the twisting of some of the constellation point, and the second shows the movement of the whole constellation off from their theoretical positions. Both can lead to the increased misinterpretation of the values, which leads to the increasing of the bit error rate.

Furthermore, the non-ideal equipment may start to twist the constellation as a function of the signal level, that is, further away from the 0-point the sample is, more it may start finding itself off the constellation point as Figure 11.19 shows.

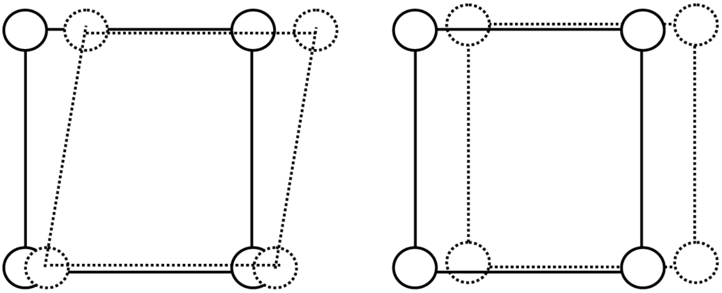


Figure 11.18 Two examples of the possible error behavior in the modulation constellation diagram.

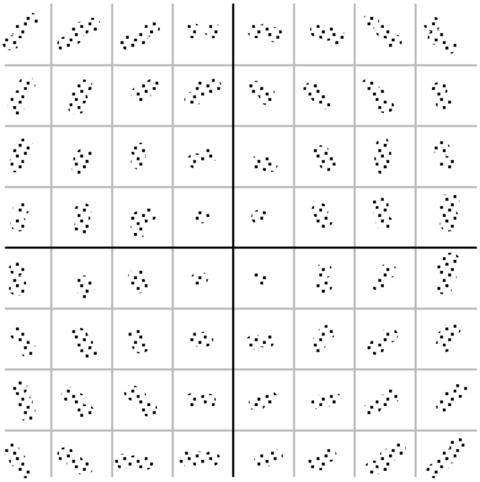


Figure 11.19 An example of the effect of the twisting constellation in the outer part of the diagram, which may be a result of, for example, component failure of the receiver.

11.3.9 LTE Performance Simulations

Development of LTE-based communication system sets major challenges for the testing process. Testing of particular protocol implementation is challenging as testing often needs to be carried out in both (simulation-based) host and target environments. There is often also a need to simulate the communication towards the overlying and underlying protocol layers as these may not be available during early phase testing.

As an example, in the CrossNet project, VTT Finland and the University of Oulu (CWC) have developed cross-layer testing and a simulation framework together with their industrial partners. The developed framework integrates existing industrial tools, the EXFO Nethawk EAST simulator, the M5 network analyzer and the EB Propsim radio channel emulator, to support a comprehensive wrap-around testing of LTE-based telecommunication systems. Figure 11.20 shows the principle of the simulator environment. The set-up is valid, for example, for the simulations of eNodeB functionality in order to investigate the performance of the system with a multitude of LTE-UEs.

11.3.10 Typical Field Test Environment

The LTE field measurements indicate a feasible performance of the system in typical radio conditions. The motivation of early technology field trials is to be able to identify inconsistent behavior and ensure that infrastructure and terminal vendors, together with the operators, identify, implement and test the necessary corrections and optimize end-to-end performance. This ensures that the actual commercial network deployments are executed as fluently as possible both as technological issues as well as the project management are considered.

The radio field trial can be located in an area where also the EPC, HSS emulator, IMS and applications are available. In typical set-up, eNodeB elements cover a relatively small area, but one sufficiently large in order to provide adjacencies to test mobility scenarios which represent

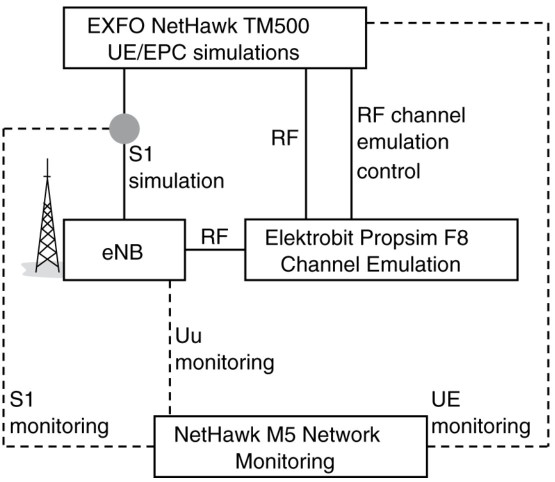

EXFO NetHawk TM500
UE/EPC simulations
S1
simulation
RF
RF channel
emulation
control
eNB
RF
Elektrobit Propsim F8
Channel Emulation
Uu
monitoring
S1
monitoring
UE
monitoring
NetHawk M5 Network
Monitoring

Figure 11.20 CrossNet LTE wrap-around testing environment.

realistic conditions of a live network in terms of interference. The eNodeB sites can be co located with existing 2G/3G sites, which normally requires the swap of the antenna systems in order to support the LTE band signal on air.

For the operation and maintenance of the eNodeBs a suitable system is needed, as it is the basis for the parameter, fault and operations handling, as well as for example, the O&M and SON feature testing. A typical LTE network set-up can be the following:

- Evolved Packet Core (EPC) – S-GW; P-GW; MME placed in a same site.
- HSS emulator for user authentication and authorization.
- IMS platform acting as a SIP server for VoIP call support.
- Application Server for the TCP/UDP streaming, FTP transfers, latency tests (e.g., ping-based), and HD video streaming.
- Internet access for internet based scenarios.

In the operator site, the supported elements can be located in the equipment room for the purpose of:

- Hosting of eNodeB elements and routers. The room can also be controlled to manage eNodeBs of the field remotely by operator's transport network.
- Hosting the O&M system equipment that are dedicated to manage LTE eNodeBs and used, for example, for O&M and SON testing.

In addition, the actual eNodeBs can be installed in the field both indoors and outdoors in such a way that they can be activated individually to form partial or complete radio coverage in the test area. In typical trial cases part of the eNodeBs can also be used as a base for the demos.

In detailed field testing, each eNodeB can be set up in such a way that it either contributes useful signals, or acts as an interference source in downlink. It should be noted that the interfering eNodeBs can be configured without S1 connections.

In a typical field testing, static, pedestrian, and vehicle radio channel types can be measured and analyzed. This requires a respective plan for the test cases, including the test set-up and procedure description, the measurement/signal generator equipment set-up and the storing of the performance indicators for the post-processing and analysis. Multiple sites are required in order to confirm the functionality of the handovers. The coverage area can be checked in the cell edge of the area both in noise-limited and interference-limited situation.

One of the important tasks is to select the LTE/LTE-A terminals. In order to make sure that the terminal itself is not the limiting factor, multiple models from various vendors should be considered which increases the statistical confidence level. This minimizes the effect of the possible non-optimal behavior of some terminals, and the results reflect thus the network performance.

As the LTE/LTE-A network is capable of delivering considerably faster data connections over the air interface, the physical end-to-end capability of the complete LTE/SAE network should be designed accordingly. The core side should have sufficient capacity in order to avoid possible bottlenecks in any of the interfaces. If limiting elements or interfaces occur, it should be known well before the actual LTE performance analysis takes place so that misinterpretations of possible lower performance figures can be avoided.

The easiest solution for the remote control of each LTE/SAE element is the centralized O&M system. If it is not available for the trial purposes, it is worth considering setting up local control systems (a PC/laptop with element manager software and direct connection to the element) in each site, which can be used remotely, for example, via a VPN/CITRIX type of solution. Such remote connections ease the configuration of the network for each test case. It is also worth noting that the possible interferer sites do not require S1 connections in order to have the interference signal on air. This avoids the additional backhaul load and saves capacity. If the eNodeBs are connected to the backhaul, for example, over a Gbit connection, a single E1 connection of PDH network or other feasible low-capacity connection is enough for the connectivity of the interfering sites to the controlling test network PC/laptop. E1/Ethernet converters can thus be used in the interferer sites.

11.3.11 Test Network Set-up

The LTE field test equipment can consist of the drive test tool to generate the data calls and the respective KPIs, a scanner to store the received power level, and a core protocol analyzer. GPS should be included in the radio measurement set-ups by default in order to correlate the results geographically. Also additional trouble-shooting tools are typically needed. These can be more specific signal and protocol analyzers in the core side, and additional analyzer elements for the test drive tools.

The LTE/LTE-A performance can be measured under varying conditions with regard to the propagation environment (dense urban, urban, sub-urban, rural, open) and user profiles (pedestrian, slow moving vehicle, fast moving vehicle, etc.). The effect of the user profile is relevant as the load figures of the network dictate the single user throughput, for example, in the average and peak load. In order to create the loading in a controlled way, general models can be applied. These models are available, for example, from 3GPP, which has defined a macro case 1 (with 500m of inter-site distance) and case 3 (with 1752m of inter-site distance) by assuming 10 users per cell as a reference.

For the test cases where interference is present, the interfering signal can be generated via the eNodeB itself if the equipment provides this type of test signal generation. A commercial eNodeB may be able to send artificial signals on the physical DL channels which can be

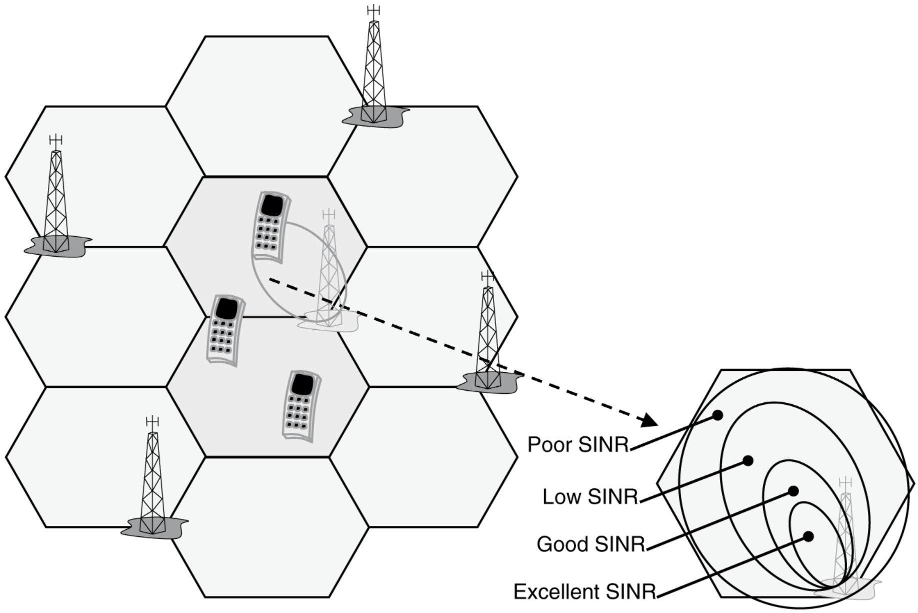


Figure 11.21 A possible field measurement set-up for the interference investigations.

configured by the so-called PhyTestInterface. As an example, generating 50% interference load means that half of the available active PRBs in PDCCH and PDSCH are used to send dummy data. For the full 100% load, all physical channels are transmitting at all time, and all the PRBs are used. Figure 11.21 shows the idea of the measurement set-up when DL interferences are created intentionally.

The uplink interference is generated by the transmitting power of UEs served by the neighboring and other cells to the one considered (Figure 11.22). The closer the interfering UEs to the cell border, the more transmitting power it will use and the lower the path loss to the victim cell which means increased interference to the UEs in the victim cell.

The uplink interference is challenging to simulate or generate in the field as it varies over time and frequency. A common approach in trials is to generate the UL interference in the field with equipment simulating LTE/LTE-A UE that can be configured in Layer 1 measurements to transmit a pseudo-random sequence on the PUSCH with a determined amount of TX Power.

The total amount of TX power transmitted by the UE is adjusted according to the path loss of the UE location and the victim cell in order to generate the desired noise level at the victim cell. As the UE is configured in Layer 1 measurements it, does not need to be camping on any interferer cell. This allows the equipment to be strategically placed anywhere in the victim's cell coverage area, increasing the flexibility of the configuration set-up and the amount of interference that can be generated. For field test cases, the location in the victim cell and L1 parameters of the UE is adjusted in order to generate the desired noise rise required for the UL loaded test cases. One example of this type of UE simulator is Aeroflex TM 500.

Uplink interference can also be generated with a Signal Generator by using the transmission patterns previously obtained. This approach is chosen for early LTE field trials as it is a field-proven concept and as it does not require HW modifications at the eNodeB site. The Vector

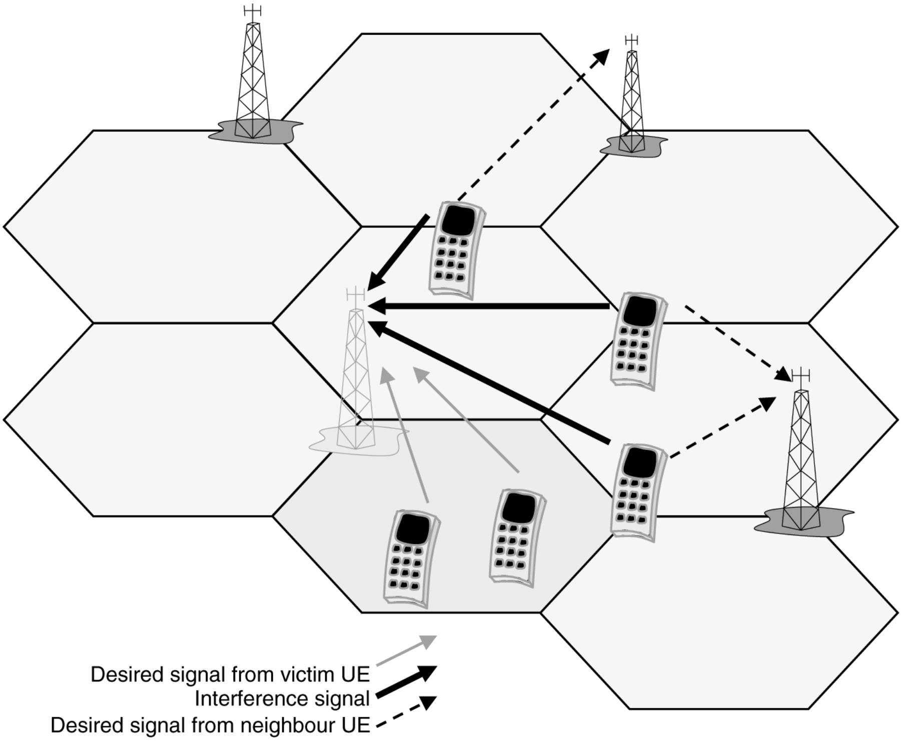

Desired signal from victim UE
Interference signal
Desired signal from neighbour UE

Figure 11.22 The idea of the UL interference creation for the trial test cases.

Signal Generator is typical equipment in the trial networks. Rohde & Schwarz SMBV100A represents this type of equipment, with an internal baseband generator which allows the generation of LTE digital standards with a sufficiently wide frequency range of 9 kHz to 6 GHz.

The uplink interference depends on the “Interfering” UE position, that is, the more the interfering set of UEs are located at the cell border, the more transmitting power they will use and also the path-loss to the victim cell becomes lower. Consequently, the produced interference to the victim cell increases.

The level of interferences and their severity depend on the operator's network performance criteria. As a basis for the DL performance indicator evaluation, the SINR (Signal to Interference and Noise Ratio) ranges can be fixed, for example, as presented in Table 11.2 for 100% DL load.

For the UL, Load Conditions (%) as a function of IoT Range can be fixed, for example, as following: 50% load => 8 dB, 100% load => 11.5 dB.

Table 11.2 Examples of the SINR criteria.

Location probability	Subjective perception	Criterion
Excellent location	Excellent SINR	$\text{SINR} \geq 20$ dB
High Location	Good SINR	$12 \leq \text{SINR} < 20$
Medium Location	Average SINR	$6 \leq \text{SINR} < 12$
Low Functional Location	Poor SINR	$0 \leq \text{SINR} < 6$
Non-Functional Location	Unacceptable SINR	$\text{SINR} \leq 0$ dB

In the LTE/LTE-A radio test set-up, it is important to decide whether a stand-alone terminal as such, or a terminal with an external antenna is used. The reasoning for the external antenna mounted, for example, on the roof of the vehicle, is that it always creates similar receiving conditions per test drive route regardless of the position of the actual terminal. The coverage area turns out to be larger, though, in this set-up compared to the terminal without any additional antenna. The benefit of the terminal without external antenna is thus close to the typical conditions of the normal users although the environment inside the car is always highly unpredictable due to the high and unequally distributed attenuation peaks.

Also it is important to take the characteristics of the terminal into account. The most limiting factor is the terminal class. Also the support of different MIMO antenna ports has an effect on the data throughput.

The successful execution of a trial requires a project plan and realistic time and resource planning. The main tasks of the trial are the following:

- Initial plan of the scope.
- Overall test plan.
- Network architecture plan.
- Detailed test plan.
- Test network deployment.
- Test case execution.
- Data post-processing and analysis.
- Reporting.

As an outcome of the trial, the functionality of the LTE system and the investigated features are evaluated. Also the performance of the network with different test cases are evaluated.

11.3.12 Test Case Selection

The overall LTE/LTE-A network testing scope may cover the following study items:

- Validation period. This is the first stage test period when the overall aim to make sure the network is correctly constructed and that the equipment is functioning as planned. This stage can include the system validation tests, site configuration and design validation tests. The outcome of this stage is information about the general coverage area, with, for examples, single user throughput in the downlink and uplink, the functioning and performance of the terminal attach and detach procedures, data streaming performance, possibly in static, pedestrian and vehicular radio channel types. The tests can include also downlink and uplink interference, when its significance is altered from non-interfered level up to the maximum level.
- Extensive testing period. This stage aims to analyze the capacity and throughput sanity testing. It can include the cases above in a more thorough way, including single user throughput in downlink and uplink, deeper data streaming by using TCP and UDP, in static, pedestrian and vehicular environment by altering the vehicular speed and interference levels. This stage also can contain MIMO and Carrier Aggregation cases, and varying capacities by altering the number of the LTE terminals. In addition, the following items are some of the examples that can be included in the test set of this stage:
    - Scheduler tests via TCP streaming by varying the number of terminals under different channel types and interference levels.

- End-to-end latency tests for the attach procedure latency. The cases can be varied under different channel types, network load levels and interference levels. The straightforward way to execute these tests is the use of PING by varying the packet size (small, medium, large). In order to increase the statistical accuracy, several PINGs can be collected by test case in order to present the latency distribution.
- Mobility and handover procedure performance test, including the measurements of the handover success rate and interruption time for different environment and traffic types (TCP and UDP streaming as well as VoIP calls), and by varying the terminal speed. The handover performance can be investigated for inter- and intra-cell and site situations. For voice calls, also Mean Opinion Score (MOS) can be measured with respective field test equipment.
- Radio features tests by varying the feature parameter settings, for example, for the Quality of Service related features, or for the uplink closed and open loop power control variants with a certain number of terminals placed in a certain constellation and moving them between the site and coverage border.
- Application performance tests, including, for example, the success rate and set-up speed of the Internet access, IMS VoIP, FTP, video streaming, HTTP browsing, Emailing and HTTP download
- Robustness and availability tests, including, for example, the attach procedure under different interference levels and the TCP streaming by adjusting the TCP window size.
- Operations and maintenance-related tests, including the functionality of the main functionalities of the tool.
- Self-Organizing Network (SON) related tests, including the validation of the correct execution of the commands and the functionality of the SON features.

11.3.13 Items to Assure

In the trial and commercial LTE/LTE-A network deployment, the maximum data speed is much higher in the radio interface compared to any other previous mobile communication networks. It is thus important to take into account all the potential bottlenecks of the LTE/SAE network in order to make sure that the end-to-end performance will be at the expected level. It can be expected that the limitations in the transport network can possibly cause problems due to the existence of several equipment, interfaces and settings where not all are under the control of the operator.

As an example, there are events in the TCP DL single user streaming which does not exceed a certain, relatively low value compared to the expected theoretical maximum data speed, even under excellent radio conditions. An analysis of the transport network element distribution along the whole communications route is thus advisable. The problem might be derived from the router data speed limitations related to each single interfaces. As an example, a data speed limitation of 45 Mb/s can be found in a single Gigabit router, which is sufficient to lower the whole end-to-end data speed. Adjusting this limit to the maximum default value that can be, for example, 200 Mb/s, can remove the problem.

The problem can also be related to the sporadic throughput fluctuations for UDP streaming in the uplink, and for TCP streaming in both directions. The fluctuations can be seen even with relatively simple tools like iPerf, which may show the sudden droppings to some lower data speed level, and slow initiation of the data transmission. This might be caused by non-optimal performance of the LTE/LTE-A terminal, especially in the initial phase. In fact, there are cases where the LTE/LTE-A terminal occasionally sends a buffer status report "empty" even if the case is not so, which can trigger the problem. Also the TCP window size can cause the problem. For testing purposes, a parallel TCP stream with the smallest TCP window size can be used in order to reach the throughput stability.

The aim of the trial phase of the LTE/LTE-A is to test the performance of the network, but in some cases this phase also reveals the behavior of some of the involved element that is not directly related to LTE/LTE-A, but needs either parameter adjustments or even complete replacement. Especially, if the core network contains "old-fashioned" solutions, they might work sufficiently well for any previous data rates, but the higher data rates of the LTE/LTE-A might reveal the limitations of those hardware and/or software.

11.3.14 Evolution of Testing

It can be generalized that the evolution changes the rules of testing in LTE/LTE-A environment. The introduction of LTE/LTE-A networks marks the end of the transition of mobile wireless networks from a traditional telephony-style circuit-switched network, which was focused on delivery of voice services, to all-IP networks capable of supporting much more efficiently data services and applications. This transition will allow operators to deliver diverse broadband services at competitive prices, because of the efficient way in which IP networks use the available bandwidth. This transition has progressed through interim technologies such as High-Speed Packet Access (HSPA), which combine circuit-switched voice with packet-based data. As an entirely packet-based technology, however, LTE/LTE-A improves the performance of mobile data services at the same time as it allows operators to package mobile services in new ways to make them suitable, from a cost and performance point of view, to a wider range of businesses and consumers than was previously possible.

Although referred to as an evolution, LTE/LTE-A represent a significant step forward. This is not only because all traffic, including time-sensitive traffic, is packet-based, but also due to the fact that LTE/LTE-A replaces the established CDMA radio technology with a new radio-access technology based on Orthogonal Frequency Division Multiple Access (OFDMA). Compared to CDMA, OFDMA will allow LTE to support higher data rates, LTE-A theoretically can support downlink data rates up to 1 Gb/s over the air for static cases, as well as lower delay and latency for data packets. In combination with the simplifying of core networks, which is a benefit of the move to entirely packet-based traffic, OFDMA is central to meeting the LTE objective of delivering more bandwidth at lower cost due to it providing better spectral efficiency. This means that fewer cell sites are required to give the same level of network capacity as previous generation technologies.

Network planners must deal with two major challenges in the successful deployment of LTE/LTE-A. The optimization of the network to meet Quality of Service (QoS) goals is of utmost importance, as well as the establishment of new models for the location and configuration of base stations in order to accurately predict the network coverage they will achieve with the new OFDM radio infrastructure. Effective optimization and network modeling will depend on reliable data obtained from accurate field tests of live LTE/LTE A networks.

11.3.15 Validation Testing

Validation testing is where a network, sub-system, or element is being tested against a fixed specification (usually a 3GGP specification, or manufacturers own internal performance specification), and normally the outcome is a pass or fail judgment to validate if the device under test (DUT) is able to meet the required levels being tested and hence is validated as compliant with the test specification. As the test specification is normally written around the operational/performance/design specifications of the DUT, it is essentially a test to validate that the DUT is correctly designed and built and operating according to the specification. Due to this close link between the validation tests and the specifications, the validation tests often have a direct correlation to the system design specifications. This can easily be seen in the 3GPP LTE specifications, comparing the TS 36.104 [12] and TS 35.141 [13] for base stations, and TS 36.101 [14] and TS 36.521 [15] for a UE. In 3GPP, the validation tests are called "conformance tests" as they are used to demonstrate conformance of the UE or eNodeB to the required minimum performance specifications.

In the mobile industry, there are two industry bodies that take the lead in providing a forum and method to assist in the validation of handsets. This was set up because of the excessive costs for handset manufacturers and network operators in performing validation of all types of handsets for all different operators. The central principle is to provide a common set of tests, test methods, and test environments, so that a new UE can be extensively tested once by the manufacturer, and the test results would be recognized and accepted by a wide range of network operators. In Europe, the lead body is called the Global Certification Forum (GCF) that today has a truly global nature. In the USA, the lead body was originally called the PCS Type Certification Review Board (PTCRB), as it was focused on the US 1900 MHz PCS band. Today it has kept the same initials, but has a wider remit to include the needs of North America in the other licensed bands. In addition, there are various national bodies that perform similar tasks on a national level for specific countries that have special needs outside of GCF. Both GCF and PTCRB tests are based on the 3GPP LTE Conformance test specifications TS 36.521 [15] and TS 36.523 [16]. They then have a set of validated test cases (where the validated tests have been independently confirmed as correctly implemented on specific test platforms) which are available to the UE manufacturers to perform their conformance testing. It is this independent confirmation on specific test platforms that provides the international recognition among the network operators of the validity of the testing. In addition, the GCF provides a common accepted framework and set of tests to perform on live network testing. Again, this reduces the amount of testing required by a UE manufacture before the network operator needs to make any evaluation or acceptance of a particular device. In recent years, there has also been a trend for some network operators to require additional testing of Inter-Operability Testing (IOT) in the laboratory before live testing on the networks. This has been driven by the increasing complexity of the network architectures and configurations, and those specific network operators have felt it necessary to add an extra level of operational tests specific to their needs over and above the functional testing described in 3GPP.

Verification tests are used during the development phase to measure the actual level of performance. So the actual level is measured, and the tests are performed in a variety of settings and configurations. The verification stage should cover the widest range of conditions, to confirm the performance in the extremes of the design. For example, a UE may be tested for output power at the lowest battery power, or the very hottest ambient temperature, to verify the performance in these extremes. But during the validation tests, then only a limited number of battery levels of temperature levels would be used. In addition, the verification tests will also include testing under negative conditions, or unexpected/not allowed conditions. Particularly for signaling (protocol) tests, it is important to verify the performance under these negative conditions. Examples of this are the eNodeB scheduler receiving inconsistent measurement reports from the UE such as very low CQI but very high RSRQ, or the UE protocol stack sending a reject message in response to a mandatory command. In this second example, a reject message is valid, but only in response to an optional command. So although the reject is made correctly, it is an incorrect time to make the reject. So, we must verify how the eNodeB protocol stack responds to this message, to ensure it has not crashed, as it would be expecting a different response from the UE.

For production line testing, it is normally a subset of the conformance tests that are made, in order to verify the correct assembly of the equipment and final check to ensure correct operation. The old phrase "time is money" applies particularly to high volume production, as time spent testing can slow down the capacity of the factory, or add significant costs due to the cost of the test system and the high value of the "work in progress" of the equipment waiting to be tested. As normally the testing is made at the end of the production process, then the full value of components and assembly time has already been invested into the equipment, and the manufacturer would like to ship the goods to the customer as quickly as possible to earn money on the work done. A long or slow production test will reduce revenues for the factory, or increase production costs. The first objectives of the production test is to verify correct assembly of the equipment, so no component is missing, mounted incorrectly, or a faulty component. This can be confirmed using simple go/no-go test. So the modulation error of the transmitter stage will be either very low if correct, or very high if incorrect. Any small variation in quality would be due to poor design or tolerance on components. So the verification testing is used to confirm the quality under all different conditions, but the production test is a simple check at only 1 or 2 levels. During the early production stages (pilot production) then more comprehensive testing may be done to establish the normal variations on the production process, but for high volume testing, then only confirmation that the value is within the production tolerances is sufficient. In the extreme example of this, the RF conformance test for a single radio band on a UE typically may take 24 hours of continuous testing to ensure compliance with all required performance specifications, but the production line test may be reduced to approximately 30 seconds of testing.

The RF test requirements for LTE are given in 3GPP standards TS 36.141 Base Station Conformance Test [13], and TS 36.521 UE Conformance Specification Radio transmission and reception [15]. These are based on the corresponding performance requirements set out in TS 36.101 [14] and TS 36.104 [12], UE and Base station transmission and reception. In addition, there are the TS36.571 series of UE Conformance Test specifications that are focused on the positioning technologies used to provide the location information of the UE using information provided by the network [13]. The test specifications TS 36.508 [18] and TS 36.509 [19] provide the detailed settings and configurations used in UE conformance testing. These are required because the network (and hence the network simulator used in testing) has many possible settings that all can influence the test results. Only by specifying the required network settings can correct and repeatable tests can be made on the UE using the test specifications TS 36.521 [15] and TS 36.523 [16].

The UE protocol test cases are written by ETSI within the Task Force TF160. This industry body is creating an implementation of the test cases using the test description language TTCN3. This test description is then readily available from ETSI web site. The test equipment manufacturers then take this TTCN3 code and implement their own specific protocol test equipment and systems, to create a test system capable of running these ETSI test cases. The selection and prioritization of the protocol test cases are made by the 3GPP working group RAN5. The selection of tests is based on the work in RAN1 and RAN2 working groups where the signaling aspects of the air interface are developed.

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12

Recommendations

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12.1 Introduction

This chapter presents recommendations for practical LTE/LTE-A deployment scenarios, including the migration path towards different LTE releases. In the beginning, LTE deployment aspects are briefly described in Section 12.2. Due to the fact, that operators are not eager to fully swap any existing legacy wireless network with the new one, GSM functionalities that allows smooth spectrum refarming and minimizing the performance gap between 2G and LTE become crucial in the multi-RAT environment. Some selected solutions are covered in Section 12.2.1. Migration specifics from TDD systems, like TD-SCDMA and WiMAX are widely described in Section 12.4. Another aspect of network evolution is the network sharing idea, involving several mobile network operators. Regardless of the actual technical solution put in place, the basic principle behind it is that certain network elements provide a service to more than one operator. These functionalities are presented in Section 12.5.

When migrating towards new technology, the hardware-related aspects have to be addressed as well, so that necessary expenditures are minimized. Hardware migration path is the subject of Section 12.6. Mobile backhaul evolution towards an all-IP environment, presented in Section 12.7, is an inseparable element of LTE deployment due to its inherent data-centric characteristic.

Deployment of the next generation communication system on top of already existing ones always raises issues related to interworking. The coexistence of different technologies brings the challenge of how to ensure efficient cooperation. LTE is no exception as it is set up in the ecosystem of, for example, GSM/EDGE and WCDMA/HSPA. Selected mechanisms are discussed in Section 12.8.

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The improvement of spectral efficiency resulting in higher capacity and UE throughputs can be driven by multiple antenna techniques. Consequently high site acquisition costs or new spectrum fees can be avoided by using the techniques described in Section 12.9.

12.2 LTE Deployment Aspects

The history of mobile networks rollouts seems to reflect the advances of mobile communication systems, the milestones of which are marked by the appearance of a new generation of wireless technologies. Taking Europe as an example, we can note that the early analog wireless networks started to appear in the mid-1980s (NMT, 450 MHz band), followed by GSM, with a major expansion around 1995 (900 MHz band, then also 1800 MHz). Next came UMTS (early 2000s, 2100 MHz band), enhanced with HSxPA technologies somewhere in the middle of 2000s. It was a common practice for mobile operators to try to cover traffic hotspots first, and then gradually extend the coverage to the whole population (which was also quite often mandated by the regulators). The same approach has been applied in the case of LTE deployment. Most of the operators started deployment of LTE networks in the high traffic demand areas such as dense urban environments. Due to higher spectral efficiency compared to GSM and HSPA, LTE has been deployed wherever possible. Unfortunately spectrum accessibility, especially in frequency bands below 1 GHz without GSM and WCDMA spectrum refarming, became a limiting factor for network-wide coverage deployment (for more details regarding LTE spectrum usage, refer to Chapter 5).

It is still not obvious if the operators intend to replace all the existing legacy wireless network with LTE technology. Nowadays LTE is used to complete and enhance the overall wireless service portfolio of the operator, but it is not yet foreseen if a full replacement of existing networks will happen.

Manufacturers offer multi-band and multi-standard terminals, capable of taking advantage of the simultaneous coverage of multiple types of wireless networks. The final decision regarding the total swap of the legacy networks is driven by the availability of voice solutions, which at the early stage of LTE standard development was unclear. Now even though a solution for VoLTE (Voice over LTE) has been developed and proven to work, mobile operators are still reluctant to switch off their GSM or WCDMA networks in the areas of LTE coverage.

The coexistence of different technologies brings the challenge of how to ensure efficient cooperation. LTE is being set up in every existing technology ecosystem – for example, in GSM/EDGE and WCDMA/HSPA. Therefore, along with LTE deployment, there is a high demand for techniques that enable optimal interworking between particular systems. Aiming to meet this challenge, a number of coexistence studies and features designed to either allow or further enhance cooperation between systems in question have been standardized by 3GPP. Selected mechanisms are discussed further in this chapter.

12.2.1 Coexistence with GSM

If the LTE technology operates in adjacent or the same frequencies as the GSM network in the given region, two major deployment scenarios could be distinguished:

- uncoordinated case, where there is no rule with respect to sites' location of GSM and LTE RAT;

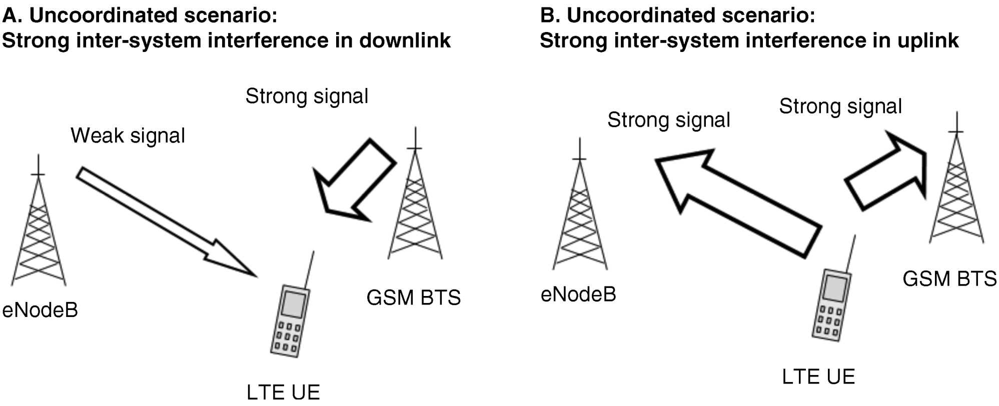
A. Uncoordinated scenario:
Strong inter-system interference in downlink
Strong signal
Weak signal
eNodeB
GSM BTS
LTE UE
B. Uncoordinated scenario:
Strong inter-system interference in uplink
Strong signal
Strong signal
eNodeB
GSM BTS
LTE UE

Figure 12.1 LTE-GSM coexistence: uncoordinated scenario.

- coordinated case, where all GSM and LTE sites are collocated and the level of inter-system interference is minimized, thanks to the inherent characteristics of such deployment and additional hardware as well as software features.

Since the level of inter-RAT interference is entirely different in these two scenarios, they have to be analyzed separately. The former option is described in Section 12.2.1.1 and the latter in Section 12.2.1.2.

12.2.1.1 Uncoordinated Scenario

The principal problem in uncoordinated deployment is presented in Figure 12.1, which is called the near-far effect, where an UE needs to increase its transmit power to reach a faraway base station receiver, causing an inadvertently high level of received uplink interference in nearby base stations belonging to the other radio technology. The same phenomenon also occurs in the downlink direction, due to distance-induced propagation losses.

Due to unmatched signal strength values coming from different systems, the carrier-to-carrier separation between the center of the edge of the GSM frequency and the LTE center frequency has to ensure that mutual interference dependency between two involved systems is minimized. Separation values proposed in [1] are presented in Table 12.1.

12.2.1.2 Coordinated Scenario

The best way of using the spectrum in dual technology deployment in the same band is the what is called the coordinated case where all GSM and LTE sites are collocated with matched azimuths of GSM and LTE sectors. In the coordinated scenario, the transmitted signals belonging to both considered radio technologies originate from the same point (roughly, as both systems may use different physical antennas), so are subject to the same magnitude of propagation losses (slight differences in the frequency band notwithstanding). Consequently, they might be received at similar levels. Moreover, mobiles close to the site location usually operate at lower power levels so they are sources of less severe interference. Therefore, in such a scenario, certain control over inter-system interference could be achieved. Hence, it is possible to reduce the needed carrier-to-carrier spacing between the GSM and the LTE in

Table 12.1 LTE-GSM carrier-to-carrier separation in the uncoordinated scenario.

LTE channel bandwidth	Carrier-to-carrier separation in uncoordinated scenario
20 MHz	10.3 MHz
15 MHz	7.8 MHz
10 MHz	5.3 MHz
5 MHz	2.8 MHz
3 MHz	1.8 MHz
1.4 MHz	1 MHz

comparison with the uncoordinated scenario where there is no strict rule with respect to GSM vs. LTE site location. The actual ratio of signal to interference in both directions will of course depend on the particular configuration of each system (i.e., initial transmit power, presence of power control, etc.). Figure 12.2 shows the interference situation in coordinated deployment cases. The LTE UE is shown, but obviously the same conclusions apply also for a GSM UE.

In order to optimally deploy a coordinated scenario, a contiguous set of frequencies refarmed to LTE have to be taken from the GSM spectrum in such a way that the outer part of spectrum belonging to the given operator will be still used by the GSM while the inner part will be devoted to LTE. Hence, legacy arrangements with respect to the assignment of frequencies at the spectrum borders between different operators will still be valid.

In order to define the proper carrier-to-carrier spacing in the coordinated deployment, the levels of interference coming from the following have to be jointly analyzed:

- from LTE eNodeB to GSM MS;
- from LTE UE to GSM BTS;
- from GSM BTS to LTE UE;
- from GSM MS to LTE eNodeB.

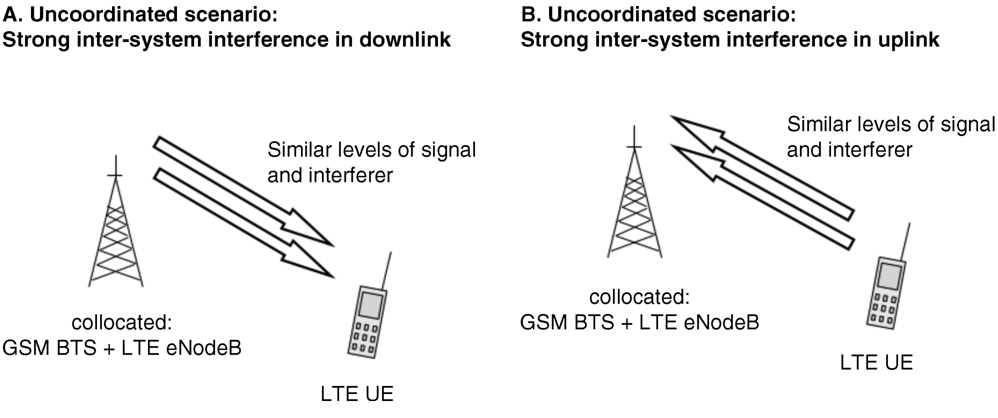
A. Uncoordinated scenario:
Strong inter-system interference in downlink
Similar levels of signal and interferer
collocated:
GSM BTS + LTE eNodeB
LTE UE
B. Uncoordinated scenario:
Strong inter-system interference in uplink
Similar levels of signal and interferer
collocated:
GSM BTS + LTE eNodeB
LTE UE

Figure 12.2 LTE-GSM coexistence: coordinated scenario.

The influence of interference coming from LTE to GSM is described in Section 12.2.1.2.1 while the counterpart effect of the GSM signal interfering LTE is presented in Section 12.2.1.2.2. For the purpose of the analysis presented in the next sections, the following nominal transmit power levels were assumed:

- GSM BTS 43 dBm;
- LTE eNodeB 43 dBm;
- GSM MS 33 dBm;
- LTE UE 23 dBm.

12.2.1.2.1 Interference from LTE to GSM

The interference dependency between interferer and victim operating in adjacent frequencies can be described with the help of ACIR (Adjacent Channel Interference Rejection) factor that is affected by both ACLR (Adjacent Channel Leakage Ratio) and ACS (Adjacent Channel Selectivity). They reflect the imperfection of the transmitter that is, transmission out of the wanted band and imperfection of the receiver that is wanted, not perfect filtering out the received out-of-band signal respectively. (Equation 12.1) describes this relationship:

$$ACIR = \frac{1}{\frac{1}{ACLR} + \frac{1}{ACS}} \tag{12.1}$$

The example calculation of the ACIR calculation in the case of GSM-LTE interference is provided, for example, in [1].

The transmission bandwidth configuration is defined as the highest possible transmission bandwidth for the given nominal LTE channel bandwidth. It could be expressed by the maximum number of available Resource Blocks [2] – as presented in Table 12.2.

The maximum signal strength of the LTE carrier outside of the channel bandwidth is bounded by the Spectrum Emission Mask (SEM) – defined separately for the downlink (eNodeB) [2] and the uplink [3]. However, the exact type of transmit filter to be used either in eNodeB or in the mobile station is implementation-specific. The way the signal is filtered in the transmitter affects the value of signal strength measured in the guard region inside the LTE channel bandwidth. Consequently, it has a direct influence on the level of inter-system

Table 12.2 Relationship between the LTE channel bandwidth and the transmission bandwidth configuration.

LTE channel bandwidth	Transmission bandwidth configuration	
	Number of Resource Blocks	Spectrum (UL/DL) [MHz]
1.4 MHz	6	1.08/1.095
3 MHz	15	2.7/2.715
5 MHz	25	4.5/4.515
10 MHz	50	9/9.015
15 MHz	75	13.5/13.515
20 MHz	100	18/18.015

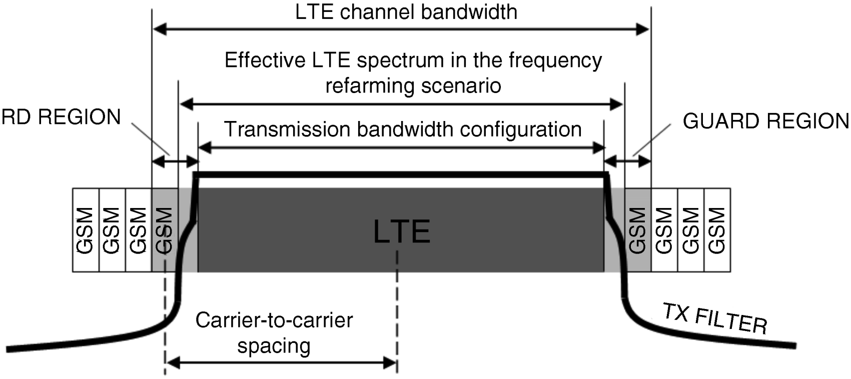
LTE channel bandwidth
Effective LTE spectrum in the frequency refarming scenario
Transmission bandwidth configuration
GUARD REGION
GUARD REGION
GSM
GSM
GSM
GSM
LTE
GSM
GSM
GSM
GSM
Carrier-to-carrier spacing
TX FILTER

Figure 12.3 LTE-GSM coexistence: carrier-to-carrier spacing.

interference coming from LTE eNodeB/UE to GSM MS/BTS if these systems operate on adjacent frequencies – as depicted in Figure 12.3. Realistic filter implementation is usually an embodiment of a trade-off between the overall LTE signal quality and out-of-band emissions.

It may be assumed that the GSM receiver could attenuate the 200 kHz signal centered at 200 kHz frequency from the serving one by 18 dB, and in the case of an interferer centered at 400 kHz frequency by 50 dB, with respect to the received interference power measured at the antenna connector that is, exactly as it was standardized for intra-GSM operation [4]. Hence, these values represent the Adjacent Channel Selectivity figures for GSM receiver.

If the level of the example LTE 5 MHz signal in most of the guard band was close to the maximum level allowed by SEM, the ACLR of LTE transmitter will be significant and consequently the ACIR in GSM MS would be as low as approximately 17 dB for 2.5 MHz GSM-LTE carrier spacing and the above-mentioned ACS figures as presented in Table 12.3.

Such a low level of ACIR could effectively degrade the instantaneous C/I in the GSM, for example, from 20 dB to 15 dB – as presented in Figure 12.4 and consequently can seriously affect the quality in terms of, for example, FER and MOS for voice transmission in GSM.

Taking into consideration, however, some realistic representation of the LTE transmit filter, the typical ACLR will be lower than the one for LTE signal power matched with SEM. Due to

Table 12.3 Carrier-to-carrier separation between GSM and LTE 5 MHz and corresponding ACIR values.

Carrier-to-Carrier Separation between GSM and LTE 5 MHz	ACIR [dB]		ACIR [dB]	
	LTE signal power matched with LTE SEM		LTE signal power with realistic Tx filter assumptions	
	LTE eNodeB interfering GSM MS	LTE UE interfering GSM BTS	LTE eNodeB interfering GSM MS	LTE UE interfering GSM BTS
2.7 MHz	35	38	48	40
2.6 MHz	32	27	43	39
2.5 MHz	17	24	38	37

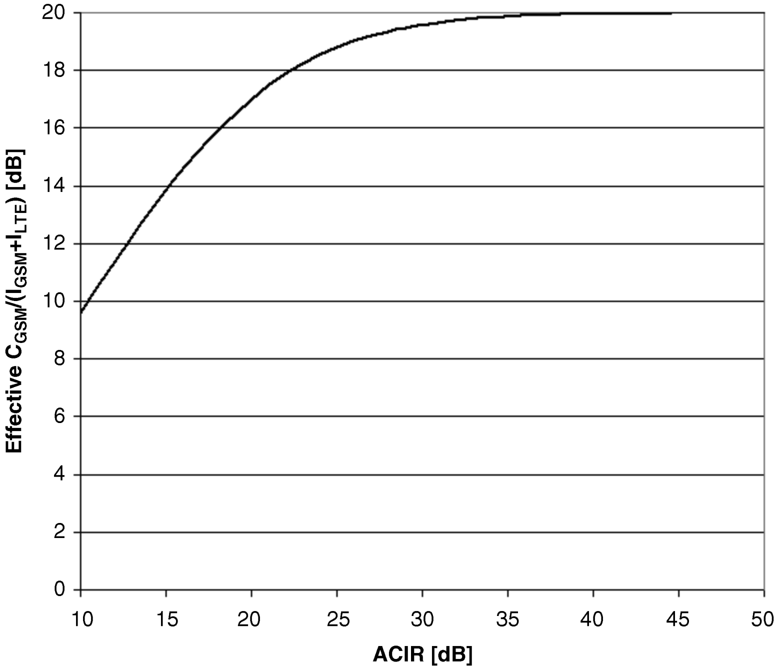

Figure 12.4 Effective instantaneous C/I for $C_{GSM}/I_{GSM} = 20$ dB.

this fact, ACIR higher than 30 dB could be achieved for 2.5 MHz GSM-LTE carrier-to-carrier spacing (refer to Table 12.3). The way this value will transform into quality the degradation of GSM depends on the C/I region where the GSM network is operating and the GSM frequency hopping scheme. In typical cases, however, this degradation should not be visible from the GSM performance point of view – in both DL and UL – especially if advanced GSM features, where resources are assigned according to the real interference situation, in the network are implemented. Particularly useful in the context of interference control in the frequency refarmed GSM network could be, for example, the Dynamic Frequency and Channel Allocation (DFCA) functionality where radio channels in terms of frequency and timeslot are assigned in an interference-aware manner. Moreover, the effect of temporal interference peaks coming from the edge of LTE PRBs could be effectively diminished with the help of regular quality-based handovers – even if the network is operating at moderate C/I. For further details on DFCA, refer to Section 12.3.7.

12.2.1.2.2 Interference from GSM to LTE

The level of acceptable interference coming from GSM depends on the acceptable quality degradation in the edge RBs that in turn is affected by, among others, the overall SINR statistics in the LTE network. Regarding the UL direction, the performance of PUCCH channels situated closest to the interfering GSM signals has to be especially considered. In the so-called sandwich allocation where an LTE band is inside a GSM spectrum, the GSM transmission will affect the PUCCH performance on both edges of the LTE spectrum and due to this fact PUCCH hopping does not provide a major countermeasure against GSM interference. In many cases, however, the observed GSM signal strength values – as measured by the GSM BTS

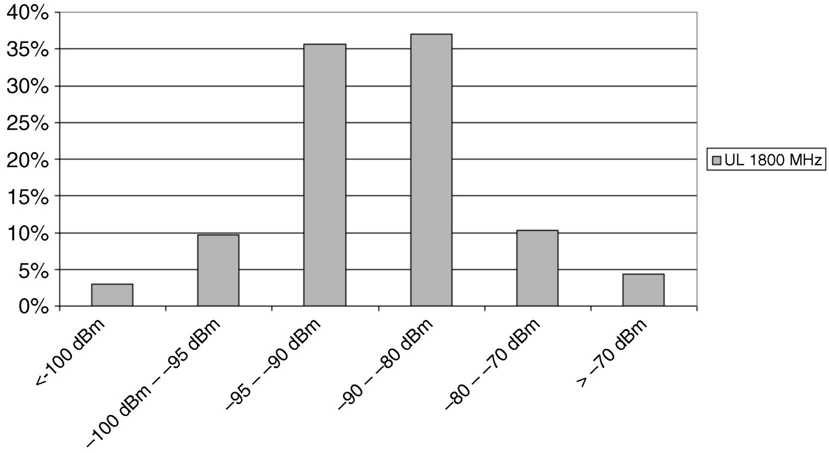

Figure 12.5 Distribution of GSM signal strength samples (uplink).

receiver – are very low. Since the GSM and LTE base stations are collocated in the coordinated scenario, it is likely that also the GSM signal strength values – as perceived by the LTE eNodeB – will be already quite low before filtering the incoming signal. Example GSM UL received signal strength distribution at BTS in 1800 MHz band in a live network is presented in Figure 12.5.

For 2.5 MHz GSM-LTE carrier spacing, the instantaneous noise level increase in the interfered UL PRB due to GSM interference, integrated over the considered 180 kHz PRB, may be of the order of few dBs for −80 dBm level – as presented in Figure 12.6 for LTE eNodeB Noise Figure equal to 5 dB [1]. However, this increase could reach even 13 dB if GSM signal was equal to −70 dBm.

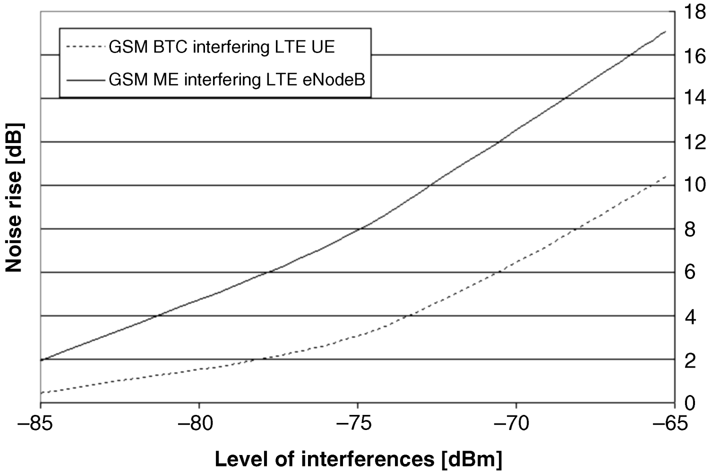

Figure 12.6 Noise rise due to GSM interference.

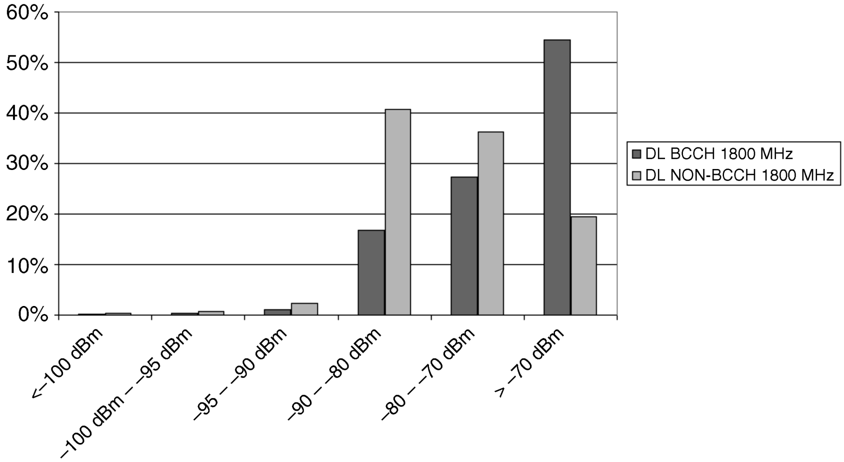

Figure 12.7 Distribution of GSM signal strength samples (downlink).

In the context of the downlink-related interference, it is beneficial to locate BCCH channels further from the LTE part of spectrum than frequency hopping channels. Performance of LTE receiver benefits from power control used in the non-BCCH GSM layer leading directly to interference reduction as perceived by the receiver. An example GSM DL signal strength distribution at the MS is presented in Figure 12.7.

For median level of DL GSM signal strength equal to −70 dBm approximately 7 dB noise rise is expected in the interfered DL PRB assuming 12 dB Noise Figure for LTE mobile [1] – as presented in Figure 12.6.

The reduction of interference level could be also achieved with the help of properly optimized Power Control functionality and a DTX feature with the help of which, during a silent period voice frames are not transmitted over the air interface. Note also that interference-aware scheduler in eNodeB should – at least up to the certain extent – compensate for the negative effect of inter-system interference coming from the GSM network by avoiding allocation of interfered frequencies. Such a need may especially arise due to, for example, instantaneous peak in the GSM voice traffic in the considered cluster.

12.2.1.2.3 Conclusions on the Spectrum Requirements

In Table 12.4, an example of carrier-to-carrier separation figures in coordinated scenario for various LTE channels is presented [5].

Table 12.4 LTE-GSM carrier-to-carrier separation requirements in the coordinated scenario.

LTE channel bandwidth	Carrier-to-carrier separation in coordinated scenario
20 MHz	9.3 MHz
15 MHz	7 MHz
10 MHz	4.8 MHz
5 MHz	2.5 MHz
3 MHz	1.6 MHz
1.4 MHz	0.8 MHz

It is expected that satisfactory performance of both LTE and GSM networks may be achieved once, for example, 2.5 MHz carrier-to-carrier separation will be applied in the coordinated scenario in case of LTE 5 MHz channel bandwidth leading to the effective LTE spectrum equal to 4.8 MHz – as described in Sections 12.2.1.2.1 and 12.2.1.2.2. The final performance figures will, however, strongly depend on many factors, such as:

- SINR conditions;
- clutter type;
- frequency band;
- load of the network;
- traffic profile time correlation between both interfering systems;
- performance of Tx/Rx filters (e.g., Adjacent Channel Protection values in GSM for interference coming from LTE that are modulated with the help of higher order modulation like e.g., 32QAM);
- transmit power levels used by the mobiles and base stations in both technologies;
- availability of features aiming at a reduction of the level of interference in the network;
- performance of the LTE scheduler in eNodeB;
- PUCCH configuration.

The reduced effective LTE spectrum requirements in the case of a coordinated scenario, compared to the uncoordinated case, directly address the problem of scarce spectrum resources available for LTE. In Figure 12.8 the availability of contiguous 900/1800 MHz spectrum chunks for given LTE channel bandwidth is presented for uncoordinated refarming scenario together with spectrum availability gain coming from coordinated deployment. The analysis was based on the spectrum assignment in 27 Member States of the European Union.

It should also be noted that, in many cases, LTE will be deployed in a coordinated way only in a part of the network, for example, LTE will be introduced in the band occupied previously by GSM only in a single cluster of cells. In such a situation, a certain geographical buffer zone has to be introduced between LTE and GSM sites using the same frequency resources. The exact size of such a buffer zone depends on many factors – most of them match the list provided above for the fully coordinated case. Hence, the resulting buffer distance will vary a lot

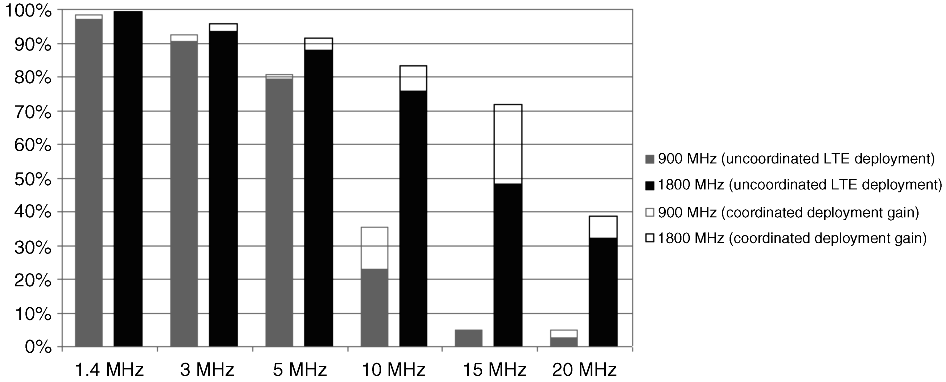

Figure 12.8 Spectrum availability gain due to the coordinated deployment of LTE.

depending on the actual network scenario. It may be even longer than 10 km in some cases in order to achieve optimum performance of both GSM and LTE network.

Another aspect that has to be considered in frequency planning is the channel raster equal to 200 kHz in GSM and 100 kHz in LTE. The carrier frequency must be a multiple of the channel raster that might prevent a certain frequency allocation even if the carrier-to-carrier separation rules were satisfied.

12.3 Effect of the Advanced GSM Features on the Fluent LTE Deployment

Deployment of HSPA in 900 MHz is ongoing in many countries. The main driver for the introduction of HSPA in 900 MHz is the better coverage provided by this band in comparison to what can be achieved in 2100 MHz. As far as 1800 MHz spectrum is concerned, it is expected that many operators will re-use that spectrum for LTE. LTE at 1800 MHz would benefit, for instance, from better coverage than could be achieved in 2600 MHz and also allow the operator to re-use its existing antenna systems. Regardless of which band where refarming will be done, there are some challenges the operators may face on the way towards mobile broadband. Given that today still a lot of voice traffic is carried over GSM, it must be ensured that refarming of the spectrum does not cause degradation to the quality of services offered by the GSM network below the acceptable limit. To address the negative consequences of the reduced spectrum left for GSM after refarming the implementation of features boosting GSM, spectral efficiency need to be considered. The hardware efficiency which is the measure of how efficiently HW resources (e.g., TRX) are used also becomes an important Key Performance Indicator (KPI) in the context of refarming. Hardware efficiency can be improved by increasing the number of users that can be carried by a single TRX. Once there is less TRXs/carriers needed to serve certain GSM traffic, then the more transmit power can be allocated to LTE or WCDMA, which may result, for example, in better indoor penetration for broadband services.

Features such as Frequency Hopping (FH), dynamic Power Control (PC), Discontinuous Transmission (DTX), Adaptive Multi-Rate (AMR), Single Antenna Interference Cancellation (SAIC), Orthogonal Sub-Channel (OSC), common BCCH or Dynamic Frequency and Channel Allocation (DFCA) are the potential means to achieve very high spectral and hardware efficiency for GSM voice traffic.

In this section the focus is on common BCCH, AMR, SAIC, OSC and DFCA features as they are the powerful tools facilitating efficient GSM spectrum refarming. Solutions addressing poor link performance of the FACCH and SACCH signaling channels are also briefly described. Their activation may significantly lower the Call Drop Rate (CDR) in the networks exploiting AMR with tight frequency reuse.

12.3.1 Common BCCH

The multiband operation offers an attractive solution for mobile network operators who are allowed to deploy their GSM networks in more than one frequency band, for example, in 900/850 MHz and in 1800/1900 MHz.

By applying a multiband operation, a good coverage footprint in a lower frequency band can be built whereas a higher frequency band can be used to provide extra capacity.

There are two options for operating a multiband network. The first requires a separate BCCH layer in each frequency band. In the second option, which is facilitated by a common BCCH

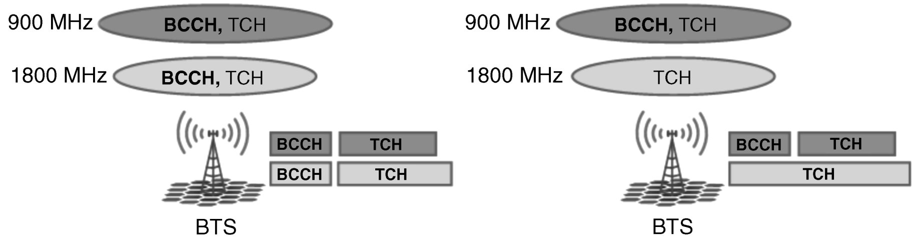

Figure 12.9 Common BCCH deployment.

functionality, only a single BCCH layer for both frequency bands is needed. This is because the common BCCH feature allows the integration of resources that is, TRXs from different frequency bands into one cell while having BCCH carrier configured in only one of them (typically in coverage layer, i.e., 850/900 MHz) as depicted in Figure 12.9. The basic requirement for common BCCH feature is that resources across all bands are co-located and synchronised.

Due to the nature of the broadcast control channel concept in the GSM standard, the spectral efficiency of the GSM networks is limited by the frequency re-use of the BCCH layer. Indeed, the lack of downlink Power Control and Discontinuous Transmission on a BCCH carrier imply that BCCH frequency re-use has to be relatively high to ensure reliable reception of the broadcast (including system information), common control and traffic channels.

Consequently, by eliminating the second BCCH layer in multiband networks, the spectral efficiency of the network can be significantly increased. The common BCCH feature might be considered an attractive solution for those operators who are planning to introduce other systems such as WCDMA or LTE into the bands that are currently used by the GSM technology. When rolling out WCDMA or LTE in the 900/850 MHz or 1800/1900 MHz bands, the available spectrum for GSM decreases which means that the low spectral efficiency of the BCCH layer will become a more relevant issue. Let us consider a dual band network scenario with a spectrum of 7.6 MHz and 9.8 MHz in 900 MHz and 1800 MHz correspondingly. Assuming that 15 frequencies are needed on BCCH layers to provide acceptable network performance, the remaining 22 and 33 frequencies (with one guard frequency between BCCH and TCH layer) are available for TCH pool – as presented in Table 12.5. We also assume a random frequency hopping scenario with tight frequency re-use pattern equal to 1/1 in that scenario.

Table 12.5 Common BCCH vs. non common BCCH deployment – TRX configuration.

	Non common BCCH		Common BCCH	
	900 MHz	1800 MHz	900 MHz	1800 MHz
Spectrum	7.6 MHz	9.8 MHz	7.6 MHz	9.8 MHz
BCCH layer	15 channels	15 channels	15 channels	0 channels
TCH layer (guard channel between BCCH and TCH layer)	22	33	22	49
max TRX configuration assuming EFL = 18%	5/5/5	7/7/7	5/5/5	9/9/9

If the allowed Erlang Fractional Load [6] for a network operating with AMR FR/HR mix 40%/60% is equal to approximately 18%, then the maximum site configuration that can be supported in 900 MHz is 5/5/5 (including BCCH TRX). If we take the same assumptions for 1800 MHz, then the maximum TRX configuration in that band will be 7/7/7. Let us consider now the implementation of common BCCH functionality with a BCCH carrier at 900 MHz. In such a case, all 49 frequencies in the 1800 MHz band can be allocated to hopping layers, to allow for cell capacity extension, that is, for the assumed EFL up to 9 TRX can be deployed in the 1800 MHz layer of the cell. 15 channels for BCCH should provide satisfactory performance on the BCCH layer. However, in some network scenarios, Antenna Hopping may be additionally required for BCCH TRX – refer to Section 12.3.5 for further details on the Antenna Hopping functionality.

If LTE 5 MHz[1] is going to be introduced in the 1800 MHz band, the spectrum for GSM services must be squeezed to 4.8 MHz so the total number of frequencies is reduced to 24. As 15 channels are required for the BCCH layer, the BCCH and TCH frequencies are separated by 1 guard frequency, eight channels only can be used to create a mobile allocation list. This means that according to the assumptions taken, only up to 3 TRX (with BCCH TRX) can be installed in the cell. Once the common BCCH feature is activated, due to lack of a BCCH carrier in the 1800 MHz, the capacity offered by that layer is significantly enhanced that is, the maximum site configuration could now be 5/5/5. It is worth noting that if as a consequence of, for example, refarming, the number of available GSM frequencies drops below the minimum required for BCCH re-use, then activation of the common BCCH functionality will be indispensable.

As one could note based on the presented example, all frequencies that do not belong to the BCCH frequency band can be used more efficiently, that is, they may be planned with a tighter re-use pattern. Moreover as only one time slot needs to be spent on broadcast channels (FCCH, SCH and BCCH) and common control channels (PCH, AGCH, RACH),[2] additional capacity is freed for voice or data traffic. For instance, with the Orthogonal Sub-channel feature activated, up to four voice users can be served on that saved timeslot.

Dual band cells with BCCH layers in each frequency band have independent pools of the SDCCH channels. Therefore, if in one of the frequency band the congestion on SDCCH layer occurs then there is no possibility of using the SDCCH resources that might be available in the second one. With a common BCCH feature, only one common pool of SDCCH channels has to be created for both layers, and due to the trunking gain, there might be fewer time slots needed for the SDCCH traffic than would have been needed in the network operating with separate BCCH layers. Consequently, the saved timeslots can be used to carry the user plane traffic. Table 12.6 illustrates the outcome of SDCCH/TCH dimensioning for selected cell configurations for both the non-common and the common BCCH case.

The main conclusion from this SDCCH/TCH dimensioning exercise is that by merging sets of the channels in the trunk pool, the capacity of the system can be increased as a result of the improvement in the trunking gain. It is worthwhile mentioning that the calculation of TCH capacity for the common BCCH scenario was done on the assumption that resources on 900 MHz TRXs and on 1800 MHz TRXs are accessible to all users in the cell. If this is not the case, that is, coverage provided by 1800 MHz layer is limited and not available in the whole cell

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[1] Actually even 4.8 MHz would be enough for LTE deployment in coordinated scenario.

[2] Provided that extra capacity for CCCH is not needed.

Table 12.6 Common BCCH vs. non common BCCH deployment – SDCCH/TCH capacity.

	Non-common BCCH		Common BCCH
	900 MHz	1800 MHz	900 MHz/1800 MHz
Configuration (only FR considered)	2/2/2	2/2/2	4/4/4
Traffic per subscriber on TCH	25 mErl	25 mErl	25 mErl
Traffic per subscriber on SDCCH	4 mErl	4 mErl	4 mErl
Blocking probability of TCH:	2%	2%	2%
Blocking probability of SDCCH:	0.5%	0.5%	0.5%
Number of channels	16 (14 TCH + 2 SDCCH)	16 (14 TCH + 2 SDCCH)	32 (29 TCH + 3 SDCCH)
Total carried traffic/no. of subscribers that can be supported	8.2 Erl/328 subscribers 16.4 Erl/656	8.2 Erl/328 subscribers	21.04 Erl/841 subscribers
Total carried signaling traffic/no. of subscribers that can be supported	2.73 Erl/682 5.46 Erl/1364	2.73 Erl/682	8.1 Erl/2024

area, then of course the trunking gain will be decreased and thus the total carried traffic will be lower.

Other benefits of the common BCCH feature are reduced number of neighboring relations which contributes to better accuracy of the measurement reports sent from the MS in CS dedicated mode. First, fewer neighboring relations means that there is more time available for measurements of a particular neighbor and therefore the measurements performed and reported by MS are more accurate. Second, the measurement report limitation (up to 6 cells with the highest RXLEV among those with known and allowed BSIC can be reported[3]) is addressed better since the limited space in the measurement report is not spent on reporting 1800 MHz neighbors. Consequently, better quality due to decreased handover rate can be expected. Moreover as the number of cells and neighbor relations will be reduced after conversion to the common BCCH-based architecture, the network operation and maintenance will be simplified.

12.3.2 AMR Full and Half Rate

AMR introduces the set of codec modes which have different levels of protection against errors and which are automatically selected according to their robustness to suit the conditions of the radio channel. Owing to better error correction capability against channel errors for the lowest AMR FR codec modes, such as 5.9 or 4.75 kbit/s, good speech quality can be provided even in poor radio conditions. For example, with AMR FR 4.75 codec mode, FER remains under 1% down to $C/I = 3$ dB, whereas approximately 8.5 dB is needed for the same performance with Enhanced Full Rate (EFR) codec.

This makes AMR FR an attractive solution that provides increased spectral efficiency for the networks operating with the spectrum, that has been narrowed as the consequence of the refarming, for example, to LTE. Moreover, as lower C/I targets can be set for AMR terminals, tighter PC thresholds can be used and therefore the overall level of interference, also

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[3] Unless enhanced measurement reporting (EMR) is implemented.

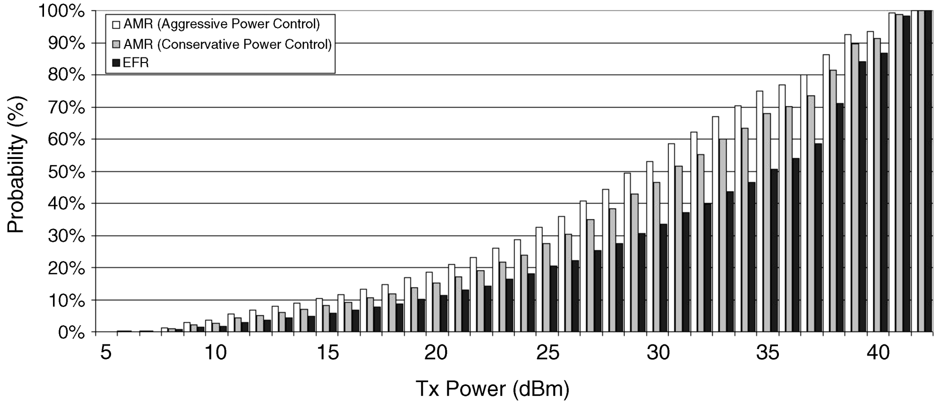

Figure 12.10 Cumulative distribution functions of BTS Tx power for AMR with different PC settings policy referenced to EFR.

intersystem one, can be minimized. Figure 12.10 depicts the BTS Tx power profile for EFR and AMR with two different set of PC parameter settings. In general, one can observe that AMR requires less power to be transmitted by BTS compared to EFR, and that with the aggressive[4] PC parameter settings, even more downlink bursts are transmitted with lower power.

The robustness of the associated control channels is another important issue that need to be addressed when improvement of the spectral efficiency in the network is highly desirable. Refer to Section 12.3.8 for further information on selected signaling enhancement features.

With AMR also another channel mode has been introduced that is, AMR HR. The gross bit rate of its codecs is only 11.4 kbps whereas for the FR channel mode, the codecs gross bit rate of 22.8 kbps is used. This entails that for the same codec mode (the highest codec mode for AMR HR is 7.95 kbps), the HR channel mode has considerably less bits for channel coding and therefore it has higher C/I requirements. The effect of AMR HR use on network performance indicators such as voice blocking rate and average Frame Erasure Rate (FER) at constant load conditions is illustrated in Figures 12.11 and 12.12. A voice call was regarded as blocked when there were no resources to serve it. Average Frame Erasure Rate (FER) was calculated as the ratio of the number of erroneous speech frames to the number of all transmitted speech frames. It can be seen that by increasing AMR HR penetration, the blocking on the radio interface was significantly lowered and no new TRX was needed to serve the traffic that was so far not admitted to the network due to lack of resources. Therefore, the use of AMR HR channel mode can be considered an efficient way to increase the network capacity and TRX use.

It should, however, be kept in mind that AMR HR requires higher C/I conditions to achieve a comparable FER performance as AMR FR. Therefore, to keep the quality of the desired level, only a portion of traffic can be served in AMR HR mode. Assuming that our quality target is an average FER below 1%, it can be observed from Figure 12.12 that at AMR use up to 60%, the average FER performance target is met. But when more users are in AMR HR mode, the average FER starts to increase and goes beyond 1%. AMR HR use can be higher at lower load operation points, as the better C/I distribution enables the AMR HR usage.

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[4] Aggressive means tighter PC thresholds are used.

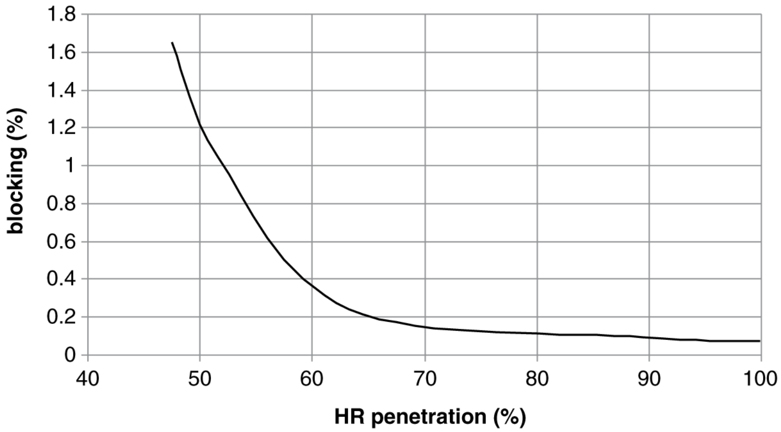

Figure 12.11 Blocking on radio interface vs. AMR HR penetration.

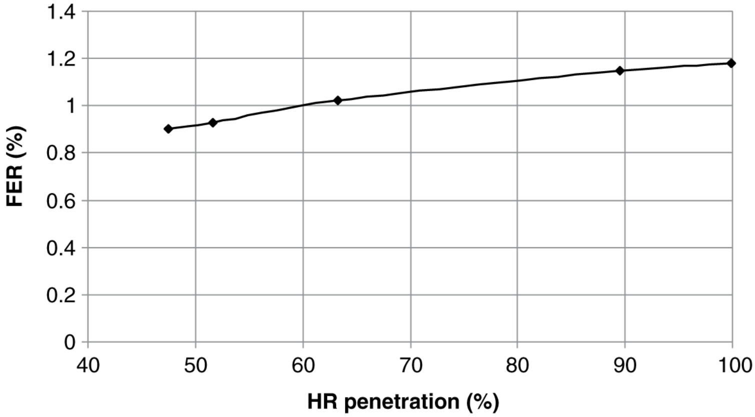

Figure 12.12 Average FER vs. AMR HR penetration.

The number of timeslots occupied in the network is reduced when the HR channel mode is used, meaning that less interference is generated on the radio interface inside the GSM system but also towards other systems that may coexist with GSM in the same band.

12.3.3 Single Antenna Interference Cancellation

Single Antenna Interference Cancellation is a generic term for single antenna receiver techniques that, by means of signal processing, attempt to cancel or to suppress interference from co-channel cells. Mobile terminals with SAIC capability can tolerate a higher interference level than non-SAIC terminals. This allows network operators to deploy a tighter frequency re-use factor which is inevitable once the GSM spectrum is going to be refarmed to LTE or WCDMA. Mobiles that indicate SAIC capability to the network are called DARP (Downlink Advanced Receiver Performance) phase 1 in the 3GPP nomenclature.

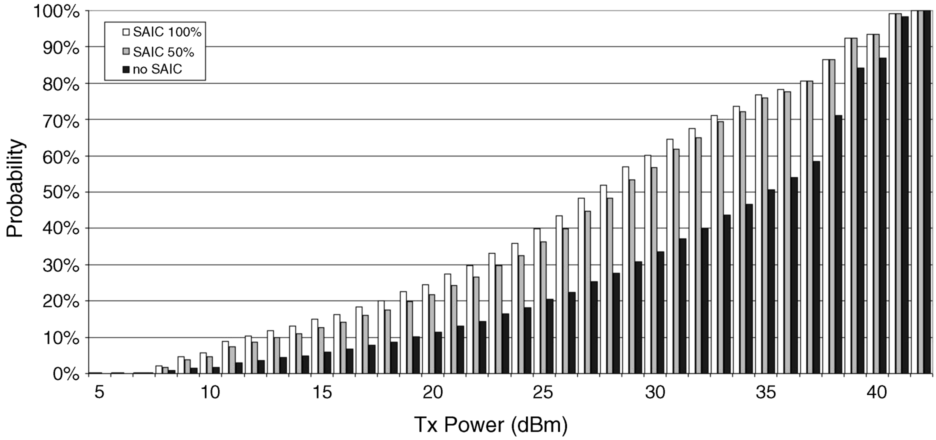

Figure 12.13 Cumulative distribution functions of BTS Tx power for different SAIC terminal penetration.

The SAIC receiver has a better Raw BER performance than a non-SAIC receiver under the same radio conditions and thus better RXQUAL values are reported by SAIC mobile stations. Since the power control is triggered by, among others, RXQUAL values, better quality samples reported by SAIC capable mobiles drive down the transmission power in the downlink direction. The decrease in the power transmitted by BTSs reduces the overall interference in the network which in turn improves the performance of the conventional non-SAIC mobiles as well.

As the SAIC terminal penetration increases, the downlink power control algorithm is able to reduce the BTS power more efficiently. This can be seen in Figure 12.13, which shows the cumulative distribution functions of BTS transmit power as the SAIC terminal penetration rate increases from 0% to 100%. One can note that the percentage of bursts transmitted with lower power increases once the SAIC-capable mobiles are present in the network. At the same time the share of bursts transmitted with higher power decreases, compared to the reference case with non-SAIC terminals only. The reduced transmission power in GSM will also contribute to the better performance of services provided by other systems, such as, for example, LTE, that are operating in the same frequency bands as GSM (for more detail about GSM and LTE coexistence, refer to [6, 10]).

In addition to investigating the effect of SAIC mobile penetration on TX power distribution, system-level simulations were performed to examine the impact of the SAIC mobiles on the system capacity. Figure 12.14 shows the percentage of dissatisfied users measured when changing load conditions in terms of EFL. Speech quality has been evaluated by means of Bad Quality Samples (the percentage of samples with FER higher than 2.1%). Simulations were run in a nonhomogeneous network cluster with an average site 2 × 2 × 2 configuration, 1/1 re-use pattern and 9 hopping frequencies defined in the MA (Mobile Allocation) list. Only the performance of the speech service on the hopping layer was taken into account, that is, the BCCH performance was excluded from this study. It can be noted that as the SAIC terminal penetration rate goes from 0% to 100%, the percentage of the BQS samples for a given load condition decreases. This gain can be exploited to keep the speech quality at the satisfactory

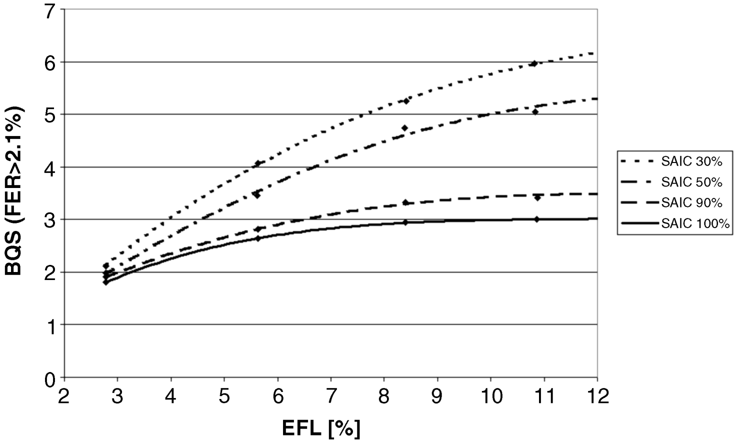

Figure 12.14 System capacity versus SAIC terminal penetration rate.

level even though EFL in the network increases as the result of the spectrum reduction in refarming scenarios.[5]

12.3.4 *Orthogonal Sub-Channel*

Voice, apart from SMS, is the key revenue-generating service in the mobile industry. In many countries, it is still the primary source of income for mobile operators and it is expected that it will continue to be an important service for many years to come. However, when taking into account that revenues from voice are declining, it is also evident that operators need to find a way to cut the costs of providing voice services over GSM network.

In order to improve the cost efficiency of the GSM voice services, an innovative feature called Orthogonal Sub-Channel (OSC) has been developed. OSC uses improvements in link performance provided by AMR and SAIC features. OSC enables up to four users to be allocated on the same radio time slot which significantly increases the BTS hardware efficiency. With AMR FR, a maximum of eight users can be allocated on the same TRX, once AMR HR is activated, the capacity of TRX can be doubled and up to 16 calls can be handled on one TRX. OSC again doubles capacity of TRX and this technique allows up to 32 half-rate connections to be supported per TRX.

This means that in contrast to a non-OSC scenario, either fewer radio timeslots or even TRXs are needed to serve the same CS traffic or a higher traffic volume can be carried on without new TRX being deployed. As far as technical realization of OSC is concerned, in the downlink it is based on QPSK-like modulation where the users are mapped onto QPSK constellations in such a way that the first bit in a QPSK symbol is assigned to one user (sub-channel 0) and the second bit to another user (sub-channel 1). The sub-channels are mutually orthogonal and can be received as a legacy GMSK signal (legacy GMSK SAIC handsets can receive them separately). In the uplink direction, however, the traditional GMSK modulation is applied in combination with 2 × 2 multi-user MIMO technique.[6] Simultaneous reception of both users at the BTS requires antenna diversity and interference cancellation algorithms to separate the two orthogonal sub-channels. Different training sequence codes have to be assigned to terminals simultaneously sharing the same channel in order to optimize the link performance, in both the uplink and downlink directions. Deployment of OSC requires mobile handsets that support AMR and SAIC. Gains from OSC strongly depend on the penetration of SAIC-capable mobiles, traffic distribution in the cell and the quality of the network which is the function of, for example, network load and frequency reuse pattern.

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[5] EFL is directly proportional to the traffic and inversely proportional to the available bandwidth.

[6] MIMO – Multiple In Multiple Out.

In the case of the AMR HR mode, although the same speech codec modes as in AMR FR mode have been defined, higher C/I values are required to achieve a similar speech performance. Therefore, transition to AMR FR is needed when voice connection in AMR HR mode suffers from bad radio conditions. On the other hand, when the quality of AMR FR voice call is good, handover to AMR HR is strongly recommended as the interference generated in the network by AMR HR connection would be reduced (fewer timeslots are on air for the same number of connections with AMR HR than with AMR FR). Moreover, there is no gain in MOS speech quality when the Link Adaptation operates already on the highest AMR FR codec mode above a certain C/I value. The equivalent MOS performance may be provided at that time by AMR HR. Similarly, OSC has higher C/I requirements compared to the AMR HR. This means that the dynamic switch between OSC and non-OSC mode according to current radio conditions is required. In addition to the quality-based criterion, due to the fact that the powers received from multiplexed OSC users in the BTS should not differ too much,[7] the dedicated mechanisms ensuring balance between RXLEV of paired OSC connections are needed. It is the task of the Radio Resource Management (RRM) algorithm to select, based on quality and path-loss criterion, appropriate users for the OSC pairing and then by means of the power control to keep their uplink RXLEV close to each other. To pair users on the same channel, the multiplexing HO, which is the counterpart of the packing HO in case of AMR FR to AMR HR transition, has been introduced. When either quality of the connection served on any OSC sub-channel falls below a defined threshold or the uplink RXLEV difference starts to be too high, the de-multiplexing HO is triggered to AMR FR or AMR HR. The de-multiplexing HO plays a similar role to the AMR HR to AMR FR unpacking HO that is, it is executed to preserve adequate speech quality when radio conditions get worse.

The OSC concept is applicable to both AMR half-rate and AMR full-rate mode offering the capability of multiplexing of up to four AMR half-rate connections on the same radio time slot in Double Half Rate (DHR) mode and up to two AMR full-rate connections on the same radio time slot in Double Full Rate (DFR) mode.

In the following, system-level performance evaluations for OSC (with only DHR mode enabled) are presented. The presented results are obtained from dynamic network-level simulations. The simulations have been run over a macro cluster, a typical urban 3 km/h (TU3) propagation model has been assumed. The network cluster consists of 123 cells from urban and suburban areas with the average configuration of 2 TRX per cell. The BCCH layer was not in the scope of this simulation campaign. A simulated scenario represents an interference-limited scenario with a tight 1/1 frequency re-use pattern and 9 TCH hopping frequencies. Penetration of SAIC-compliant terminals was set to 50%. Mean call duration was fixed at 90 seconds. Power control and discontinuous transmission (DTX factor 50%) in the uplink and downlink were enabled.

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[7] RXLEV balance between two connections occupying paired OSC-0 and OSC-1 sub-channels must be maintained within a certain dB window (e.g., 10–15 dB) for sufficient quality.

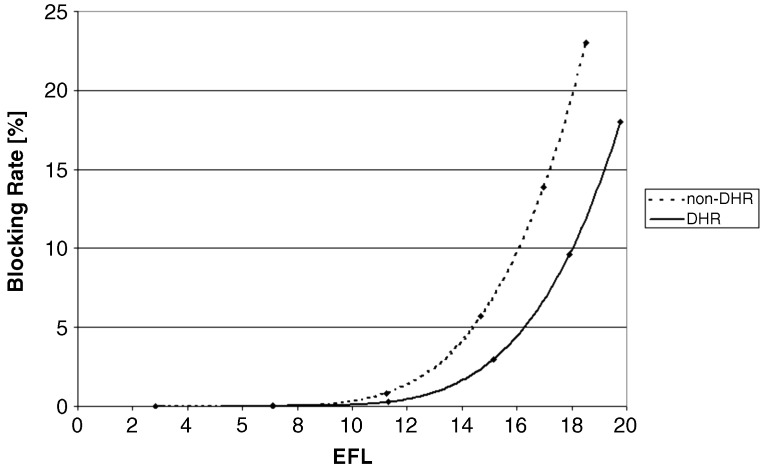

Figure 12.15 Blocking rate in non-OSC and OSC scenario.

The blocking rate was monitored to evaluate capacity gains resulting from OSC activation. A call was considered as blocked when all available traffic channels in a cell were in use and a new connection could not be established. In the simulated scenario, approximately 15% of the capacity gain has been achieved as can be noted from Figure 12.15. This improved HW efficiency provided by OSC has been achieved at the cost of only a slight speech quality degradation that has been evaluated in terms of average Frame Erasure Rate (FER) (see Figures 12.16 and 12.17).

Owing to increased HW efficiency with OSC, fewer radio time slots are needed to serve the same traffic as in the non-OSC case. Figure 12.18 shows the time slot occupation ratio as a

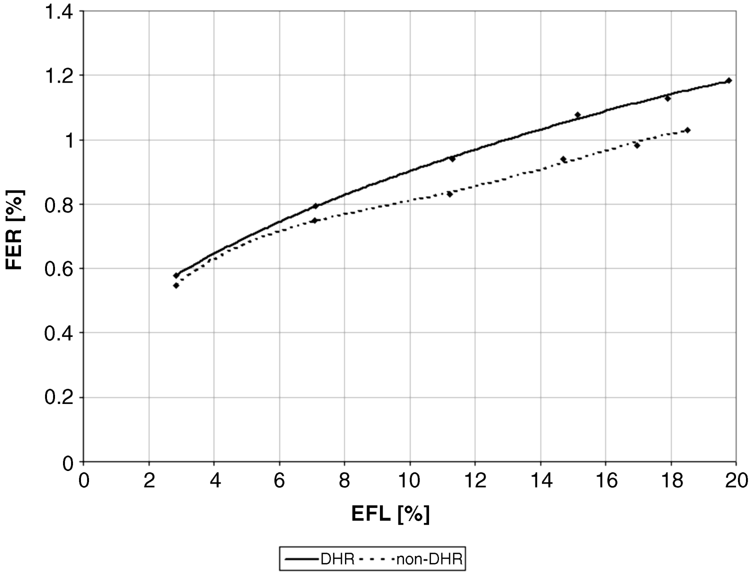

Figure 12.16 Average downlink FER in non-OSC and OSC scenario.

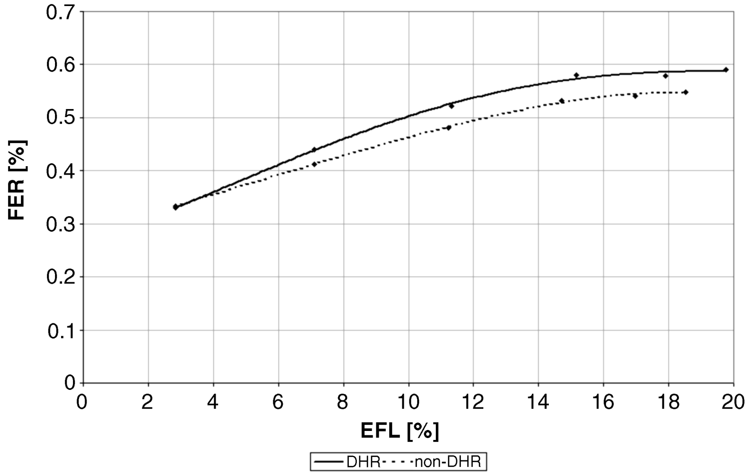

Figure 12.17 Average uplink FER in non-OSC and OSC scenario.

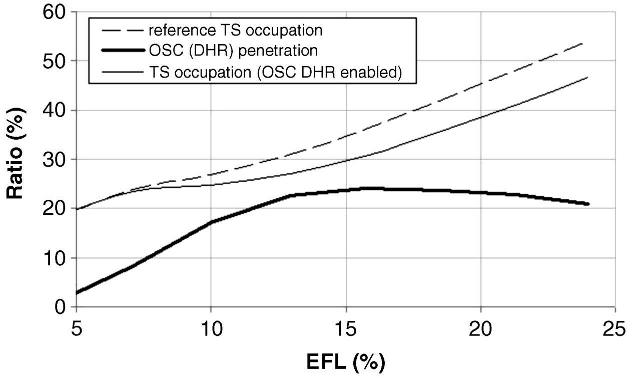

Figure 12.18 Timeslot occupation in non-OSC and OSC scenario.

function of the network load in terms of the Erlang Fractional Load. The reference TS occupation denotes a scenario with AMR only and variable AMR HR penetration reaching almost 100% under very high network load conditions. Studied here was the configuration of two hopping TRXs per cell and 1/1 frequency hopping with nine frequencies in MA list. It can be observed that the activation of the OSC decreases the TCH time slot occupation by around 15% at a certain OSC penetration rate. Consequently, it contributes to a reduction of interference caused by the GSM system to LTE in both the uplink and downlink directions.

In order to verify the impact of SAIC mobile penetration on the DHR mode use and therefore the magnitude of OSC gains, additional simulations were performed. The results shown in Figure 12.19 indicate that the proportion of the users that can be handled by the network in OSC mode depends on the amount of SAIC capable terminals. The higher the SAIC mobile penetration is, the more potential candidates for DHR multiplexing can be found in the cell and hence for the same multiplexing/de-multiplexing criteria a higher DHR use may be achieved. It can be seen that overall cluster DHR use has increased from approximately 20% to 43% as the

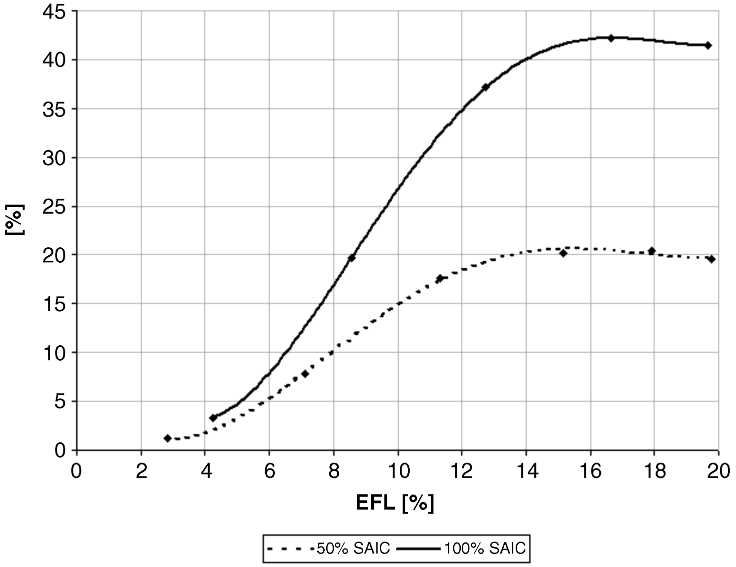

Figure 12.19 DHR use for 50% and 100% penetration of SAIC mobiles.

penetration of SAIC terminals reached 100% (i.e., there were no conventional receivers in the network). Higher DHR use translates to the lower blocking probability (see Figure 12.20) for the same network load or more traffic that can be offered to the network without a negative impact on the blocking rate.

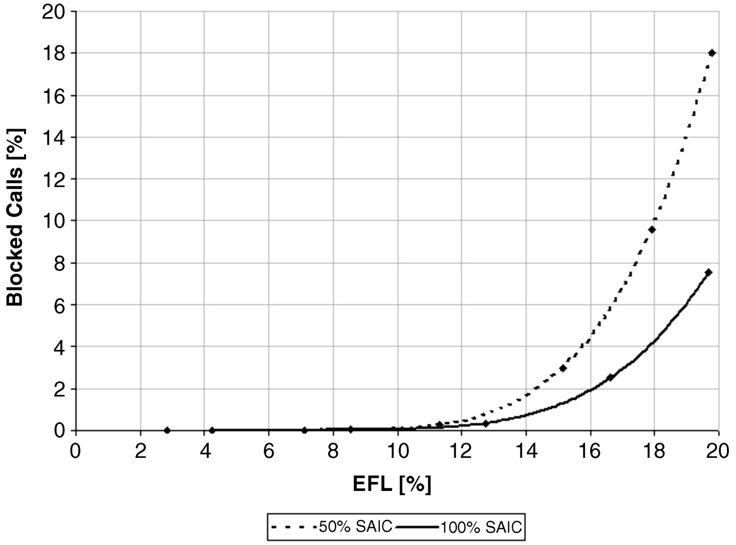

Figure 12.20 Blocking rate for 50% and 100% penetration of SAIC mobiles.

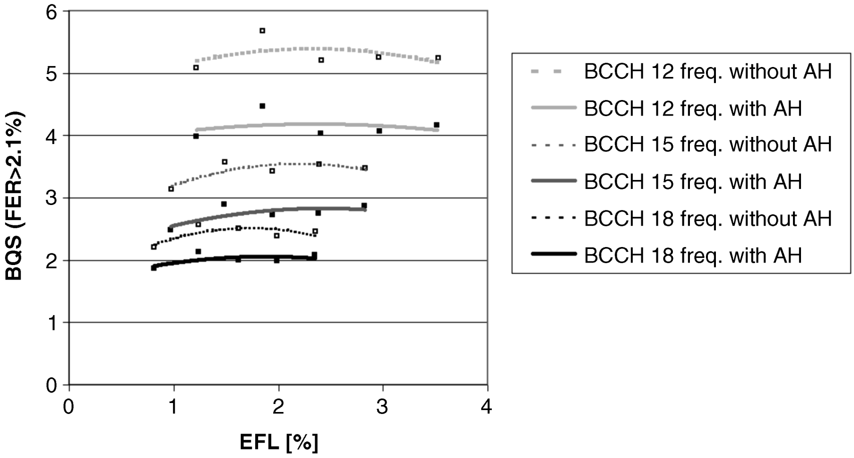

Figure 12.21 Antenna hopping performance.

12.3.5 Antenna Hopping

The well-known frequency hopping functionality in the GSM network introduces a certain frequency diversity and consequently directly improves the link level resilience against deep fading dips. Different fast fading profiles of various frequencies in the hopping scheme help to achieve decorrelation of fading between subsequent bursts and hence improve the link level performance. Deep fading could also be minimized by alternating the transmit antenna on a burst-by-burst basis which introduces certain space diversity and artificial Doppler spread, leading to decorrelation of fast fading profiles. Such a scheme is used in the antenna hopping functionality.

Since frequency hopping and antenna hopping benefit from the same radio propagation effect, the gains of these two features are not cumulative ones. In fact if the number of hopping sequences is high, the gain of antenna hopping on top of frequency hopping is very limited. Therefore, antenna hopping is especially applicable in the BCCH layer where standard RF hopping is not used.

In Figure 12.21 simulation results for antenna hopping for various BCCH plans deployed in a real network scenario consisting of 123 cells with 100% FR are presented.

Thanks to antenna hopping, the performance of the BCCH layer consisting of 15 frequencies may be nearly the same as for the standard BCCH scheme with 18 frequencies without antenna hopping. Moreover, with the help of antenna hopping it might be even possible to achieve satisfactory Frame Erasure Rate (FER) performance expressed by Bad Quality Samples (BQS (FER>2.1%))[8] that is, BQS lower than 5% for very tight BCCH reuse with 12 frequencies.

A significant improvement in the downlink BCCH quality may enable tighter frequency reuse plans in the BCCH layer what would be beneficial in the frequency refarming scenarios since more frequencies could be refarmed to other technologies. In some cases, part of the saved frequency carriers may supplement the list of hopping frequencies in GSM.

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[8] BQS (FER > 2.1%) represents the ratio of 1.92 s speech samples with frame erasure rate (FER) higher than 2.1% (more than two erroneous frames out of 96); BQS (FER > 2.1%) = 5% means that there was more than twobad frames in 5% of all observed 1.92-second intervals.

Consequently, overall GSM quality would not suffer from spectrum reduction in network migration scenario.

On the other hand, quality gains due to antenna hopping facilitates also OSC DHR introduction in BCCH layer (for an OSC DHR description, refer to Section 12.3.4).

Antenna hopping functionality may be also treated as a complement to the Dynamic Frequency and Channel Allocation (DFCA) feature since it provides direct quality improvements in BCCH layer where DFCA does not operate. For further details on DFCA, refer to Section 12.3.7.

12.3.6 EGPRS 2 and Downlink Dual Carrier

In order to reduce the PS performance gap between GSM and LTE, there is a strong need to introduce performance boosters in the GPRS/EDGE network that will help to increase the throughput as perceived by the user attached to the 2G network. This is especially needed if contiguous LTE coverage is not available (which would be the most common case in the first LTE deployments) and simultaneously a significant number of LTE UEs also have GSM capability.

Such PS performance boosters, namely, Downlink Dual Carrier (DLDC) and EGPRS-2 were introduced in 3GPP Release 7. With the help of DLDC functionality, DL TBF for PS transmission may be allocated on two independent carriers, not on one – as in previous releases. Hence, an achievable peak downlink throughput could be doubled.

In EGPRS-2, the physical layer of EGPRS was changed. New modulations (up to 32QAM) and coding schemes were defined and grouped into two levels: EGPRS-2A and EGPRS-2B. Moreover, turbo codes and higher symbol rate were also incorporated in the EGPRS-2 functionality. In the uplink a wider than standard linearized GMSK pulse shape was also defined. Work on pulse shape improvements over legacy LGMSK in DL direction has not been concluded yet in 3GPP [7]. For further details related to these functionalities, refer to [6].

The EGPRS-2 theoretical peak throughput per timeslot could be doubled in comparison with legacy EGPRS transmission and moreover it could work on top of Downlink Dual Carrier functionality. EGPRS-2 also improves delays as perceived by the user. In Figure 12.22

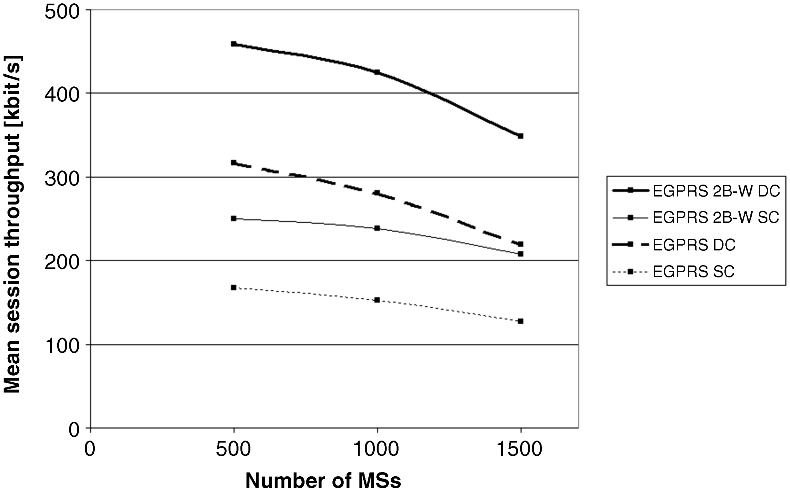

Figure 12.22 Performance of EGPRS 2 together with DLDC.

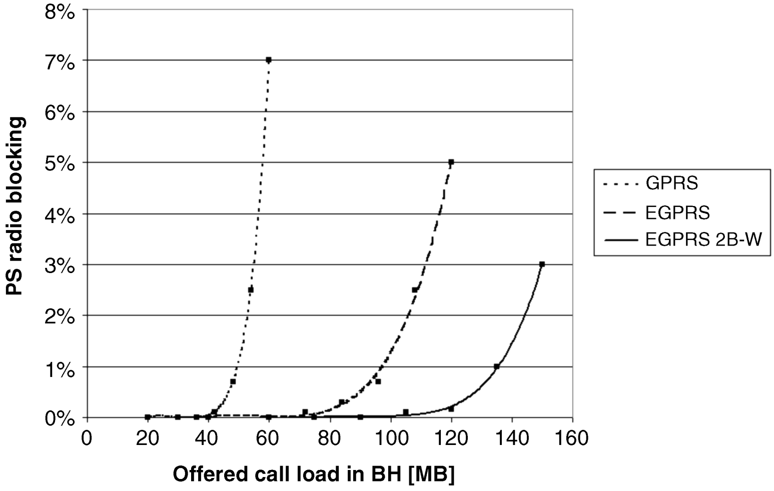

Figure 12.23 PS radio blocking – EGPRS 2 vs. legacy systems.

simulation results for EGPRS-2B with wider pulse shape (EGPRS 2B-W), together with DLDC, are presented. Simulations were performed in the BCCH layer consisting of 17 frequencies in a real network scenario with 112 cells in a SMART simulator (for a further description of a SMART simulator, refer to [6]).

In the simulated scenario, the mean session throughput in heterogeneous network deployment could be nearly tripled in comparison with the legacy EGPRS if both EGPRS-2 and DLDC are implemented together, which makes the enabling of these two functionalities attractive in the multi-RAT environment.

Thanks to DLDC and EGPRS-2, PS resources and consequently system throughput may be distributed more efficiently between network users, leading to either a significant improvement in mean user throughput (as presented in Figure 12.22) or a higher system load without compromising the users' perceived quality. In Figure 12.23 a simulated PS radio blocking in a single cell for HTTP service is presented. Any given user performs 5 HTTP transactions, each of which leads to 1 MB data download followed by a short time break of 12 seconds which aims to model the real user behavior while browsing web pages.

Thanks to EGPRS-2B, the offered cell load could be increased by approximately 35% while maintaining the PS radio blocking at the same level as in the pure EGPRS scenario (assuming the same amount of resources to be used by PS services).

Apart from the hardware efficiency improvements presented above, EGPRS-2B may be also regarded as a spectral efficiency feature. In Figure 12.24 the mean session throughput for EGPRS-2B (with wider pulse shape) as well as EGPRS service is depicted for the BCCH layer with 12 frequencies and for the TCH layer (1TRX/cell) with tight 1/1 re-use and only six hopping frequencies.

According to the simulation results, usage of EGPRS 2B-W compensates for the limited number of frequencies available for PS transmission in the TCH layer and helps to achieve a better or similar performance in terms of throughput in comparison to the EGPRS used in the BCCH layer. This advantage of EGPRS-2 functionality will be especially beneficial in network migration scenarios where part of the GSM spectrum is refarmed to other technologies such as

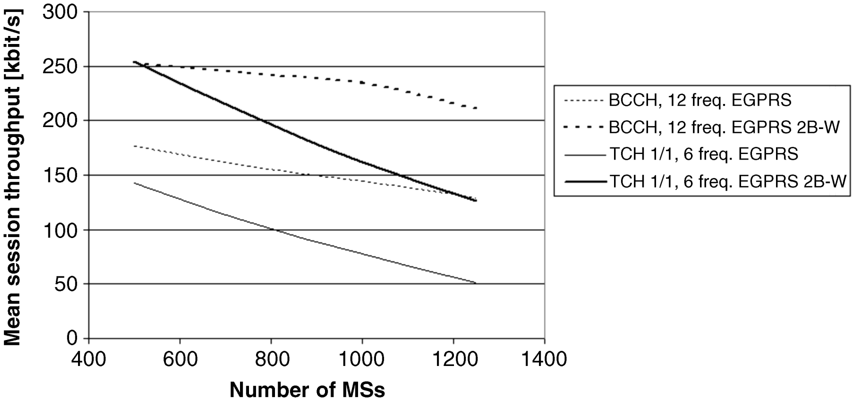

Figure 12.24 Spectral efficiency of EGPRS 2.

LTE and will help to ensure the proper performance of the GSM network operating in a reduced spectrum allocation.

12.3.7 Dynamic Frequency and Channel Allocation

The radio frequency spectrum is a precious, limited natural resource for which demand fairly exceeds supply. The notion of spectrum scarcity means that spectral efficiency (that quantifies traffic volume that a network can serve per MHz) is a critical metric and the techniques that allow re-use of the existing spectrum in the most efficient way have always been a top priority for mobile network operators. Dynamic Frequency and Channel Allocation as an advanced spectral efficiency solution is essential, especially in the case of spectrum refarming for WCDMA/HSPA or LTE needs.

Contrary to standard random frequency hopping (that averages the interference throughout the network), the Dynamic Frequency and Channel Allocation (DFCA) does not randomize interference but controls them and hence significantly increases spectral efficiency. The control of interference is achieved by means of cyclic frequency hopping and inter-site synchronization.

With DFCA, the actual frequency of each TRX comes from the MA list and the assigned MAIO and is changed to another one, every TDMA frame. The synchronization between the frames of the TRXs ensures that the two calls using the same MA list will always use different frequencies: they use the same timeslot number and the same MA list but they do not interfere because they have different MAIOs allocated. If these TRXs belong to the same site, they are synchronized as usual. If the TRXs belong to different sites, they need to be synchronized in order to control the interference between them.

DFCA allocates radio channel as a combination of timeslot, MA, MAIO and TSC. Additionally, it calculates an initial DL and UL power reduction to ensure that the only required power level is used from the very beginning of the connection (before standard power control action). When a channel is to be allocated for an incoming call (call set-up or handover), DFCA evaluates all the possible candidates and then selects the most suitable channel. For this reason, the C/I is estimated for each available radio channel. The aim is to choose the best channel, in terms of both incoming interference (the disturbance that the new call would be suffering) and outgoing interference (the disturbance that the new connection would cause to calls in the other cells). C/I for potential target channel is estimated based on the mobile measurement reports. For the cells not included in the latest measurement report, C/I estimation is obtained by collecting long-term neighboring cell Rx Level measurement statistics from all mobile measurement reports in a cell. These statistics are stored in a BSC as the Interference Matrix (IM). In this way the DFCA is able to estimate C/I for all the potentially interfering cells, even if some of them were not included in the latest measurement report. For the neighboring cells that are included in the latest measurement report, C/I is estimated, based on the data provided by the mobile Rx Level value of the serving and neighboring cells as well as the applied DL power reduction. For the rest of the surrounding cells, the statistical C/I estimation (data from the interference matrix) can be used.

There are four C/I estimations calculated for each available radio channel. The incoming C/I describes the interference coming from existing connections that would affect the new call, for which the channel assignment is being performed. The new connection may also cause interference to existing calls using the same or an adjacent radio channel. This is examined by determining the outgoing C/I for every potentially affected existing connection. Incoming and outgoing interference are estimated separately for the downlink and uplink directions. The C/I estimation relies on the fact that the interference relations in a DFCA network are stable, predictable and controlled, due to site synchronization and cyclic frequency hopping. The C/I is determined by combining information from measurement reports, the interference matrix and the BSC radio resource table where the current status of radio resources occupation is stored. The difference between the estimated C/I and the target C/I value (required C/I) is calculated. This difference is computed for incoming and outgoing C/I for both UL and DL directions. Among these four C/I differences (calculated for the strongest interferer), the lowest one is determined. This most restrictive C/I difference is then used in the channel selection procedure.

Having determined the most restrictive C/I difference for all the candidates, the channel with the highest C/I difference is checked against the soft-blocking limit. The soft-blocking limit is the configurable threshold in dB to ensure that the new connection would not generate or would not suffer from too strong interference. A channel request which breaks the soft-blocking limit is served on non-DFCA TRXs of the cell (typically BCCH TRX). This soft-blocking validation is an admission control mechanism in DFCA networks.

DFCA also takes care of the training sequence code assignment. After a suitable channel has been found, the BSC determines the most appropriate TSC by checking all the interfering connections. The BSC searches for the training sequence code (TSC) that has been used by an interfering connection characterized by the highest C/I relation. This means that for the selected MA, MAIO and time slot combination, the C/I differences are examined TSC by TSC. Training sequence code selection aims at avoiding the worst-case situation where a significant interference source uses the same training sequence code as the new connection. Conflict with a significant interferer would cause the receiver to obtain the incorrect channel estimation and consequently would lead to link-level performance degradation. For that reason, the TSC used by the connection with the highest C/I difference is selected by the DFCA algorithm, to guarantee that the new connection will not suffer from undesired effects coming from TSC cross-correlation.

Presented above, the channel selection process is used for any service type (e.g., EFR, AMR HR, SDCCH, (E)GPRS) with its service-specific C/I target and C/I soft-blocking thresholds.

DFCA allows the setting of different QoS requirements (by means of different C/I target thresholds) for different types of services. This is very important since the robustness of these services against interference varies significantly due to different channel coding. For example, the AMR connection can tolerate a much higher interference level than the EFR one while still maintaining a comparable performance in terms of speech quality. For (E)GPRS services, higher C/I requirements are usually set to benefit from higher modulation and coding schemes (MCS). Additionally, for SAIC-capable mobiles able to provide sufficient quality at higher interference levels, a special configurable offset is applied to connection-specific C/I target and C/I soft-blocking thresholds.

In high network load conditions, most of resources are occupied and DFCA has not much freedom in channel selection. Therefore, it is beneficial to increase the half-rate usage in the high load scenario even if there are still enough hardware resources available in the cell. For that reason the forced half-rate mode has been introduced with DFCA. Forced HR mode is a means of channel rate selection between full rate and half-rate, based on the average of the estimated incoming DL C/I values. The average DL C/I ratio provides a good benchmark of the load of DFCA frequencies and hence it can be used to force HR allocation. Forced HR mode is triggered if the averaged C/I drops below configurable threshold.

The main advantage of DFCA compared to other channel allocation methods is that DFCA dynamically adapts to changing interference conditions. By controlling interference, the DFCA functionality provides the best possible means of radio channel allocation with the highest possible quality.

The performance of the DFCA has been evaluated by network-level simulations comparing the DFCA performance with a reference case that used random frequency hopping with 1x1 re-use. The real network scenario was created by importing a network layout of a real network in a city center and its surroundings. Uneven traffic distribution was used to achieve the cell loads from the real network. In both the reference and the DFCA cases, nine hopping frequencies were used. Considering that twelve frequencies were used for the BCCH layer, 4.2 MHz in total was used in that network.

As presented in Figure 12.25, activation of the DFCA feature allowed an increase of HR usage by 35 percentage points. This gives a huge benefit in terms of hardware efficiency as the same traffic can be served by 2/3 number of TRXs (compared to the nominal number of hardware resources).

With RF hopping, HR penetration becomes saturated at the level of 63%. Above this level, radio quality becomes so poor that it does not allow further HR allocation, even though load

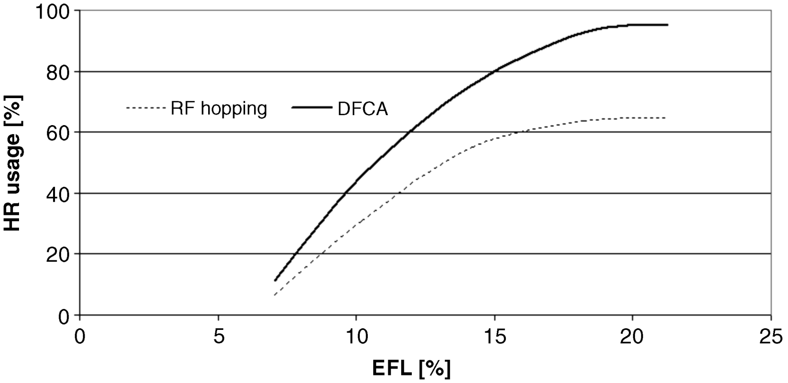

Figure 12.25 HR usage in the case of DFCA and RF hopping.

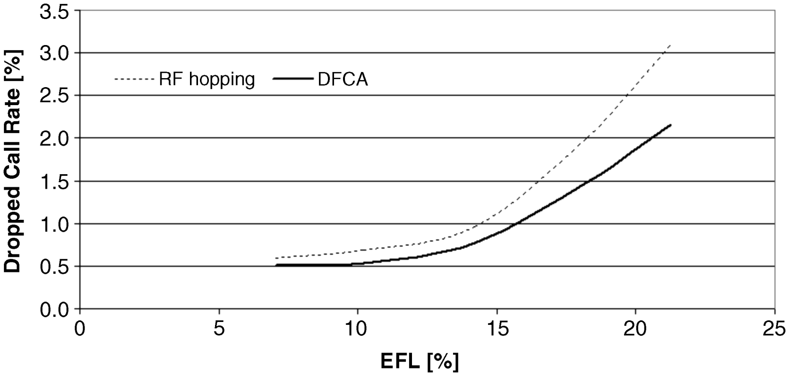

Figure 12.26 Dropped Call Rate in the case of DFCA and RF hopping.

conditions are fulfilled. With DFCA, much better radio conditions allow 95% of HR usage (only very small portion of calls cannot be allocated as HR due to bad radio quality).

Higher HR usage is possible thanks to better overall C/I conditions due to the interference control ensured by the DFCA. On top of this, the other Key Performance Indicators (KPIs) such as Dropped Call Rate (DCR) and Bad Quality Samples (BQS) decreased.

As illustrated in Figure 12.26, simulation results show that DFCA fairly reduces DCR (approximately 20% quality gain at 14% of EFL). In addition to the improved DCR, the simulations clearly indicate an improvement in terms of Bad Quality Samples. Bad Quality Samples were calculated as the percentage of SACCH frames with Frame Erasure Rate above 2.1% of all samples. This definition means that BQS reflects speech quality that is perceived by the end user.

BQS of 5% is considered the outage threshold above which the end user starts to experience unacceptable speech quality. At 13% of EFL, a simulated network with RF hopping hits the BQS thresholds of 5%. At the same traffic load but fairly higher HR penetration, DFCA provides 20% better DL speech quality, that is, a BQS of 4% (Figure 12.27). The number of

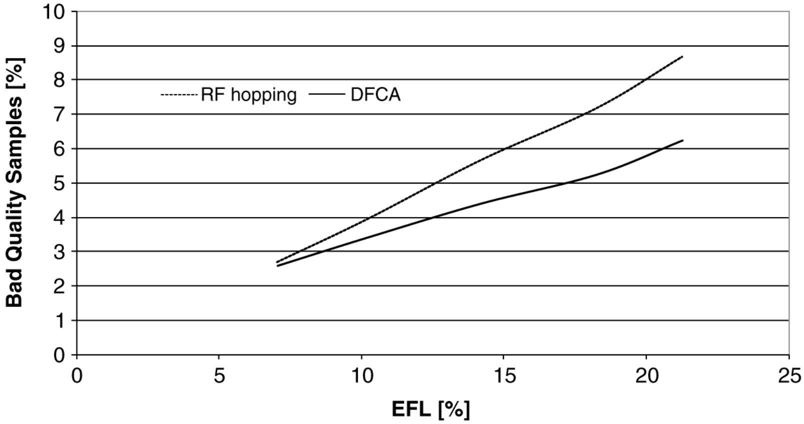

Figure 12.27 DL Bad Quality Samples in the case of DFCA and RF hopping.

measurement samples with bad quality is correlated to the level of interference that is reduced by DFCA, which allocates a channel affectin ongoing calls in the least harmful way.

The performance figures from simulations show that the DFCA functionality provides significant spectral efficiency gains. This means that the DFCA allows operators to serve the same traffic with the squeezed frequency spectrum while keeping quality at satisfactory level.

In this way DFCA is the best spectrum efficiency booster that allows spectrum refarming for the other technologies such as WCDMA/HSPA or LTE.

12.3.7.1 Dynamic Frequency and Channel Allocation and Orthogonal Sub-Channels

DFCA is a spectral efficiency feature that improves the quality of the network throughout the intelligent, interference-aware allocation of radio resources. Improved quality of the network results from the fact that, first, DFCA assigns a channel that provides sufficient performance for given service. Second, DFCA cares that the impact of the connection to be allocated on the selected channel towards the ongoing ones is minimized. As described above, OSC has higher quality requirements compared to, for example, the AMR HR, and to trigger the pairing of users into OSC mode both of them have to be in good radio conditions (among other criteria).

Figures 12.28 and 12.29 show the downlink and uplink RXQUAL distribution collected from the network cluster with and without DFCA activated. It can be noted the percentage of good RxQual samples significantly increased after DFCA activation. The number of measurement samples with good RxQual results from the level of interference that is reduced by DFCA.

If we assume that the OSC de-multiplexing threshold is set to RXQAUL = 4, then the percentage of RXQUAL samples at which OSC may operate changes from 85 to 97% for the uplink direction and from 75 to 88% for the downlink which is the limiting link here. Consequently the boost in the good quality samples may be converted to higher OSC penetration in the network. Therefore, the combination of DFCA and OSC features may

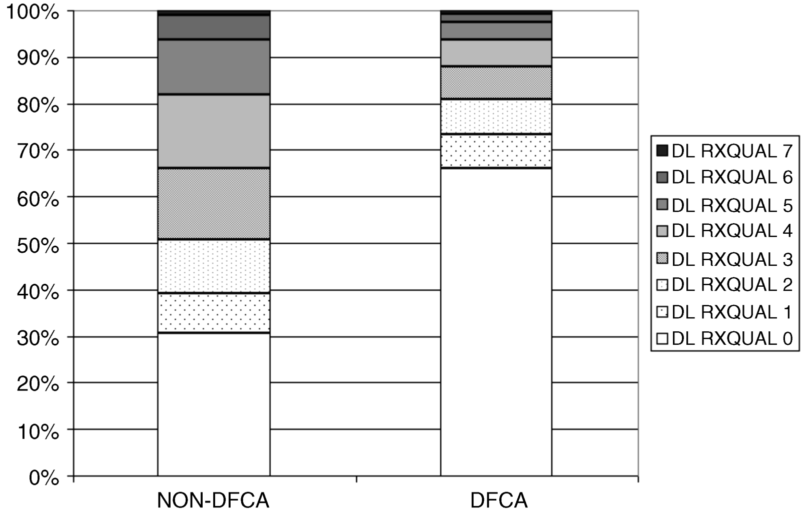

Figure 12.28 DL RXQUAL improvements due to DFCA.

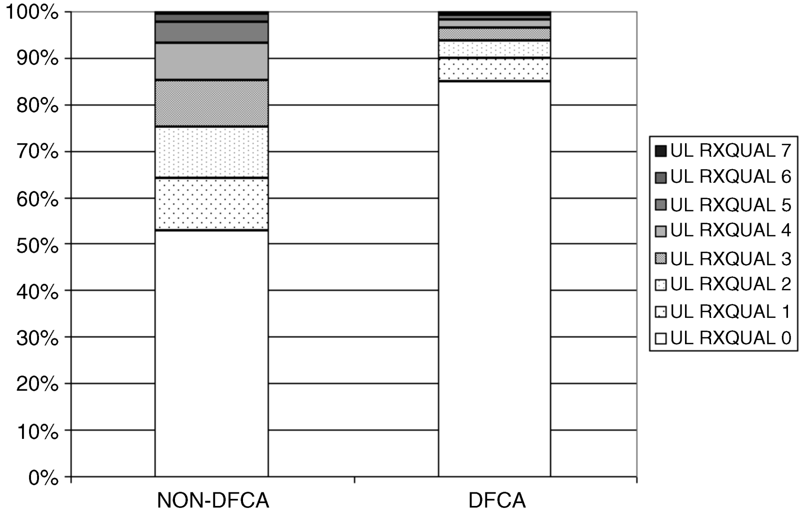

Figure 12.29 UL RXQUAL improvements due to DFCA.

be considered a very attractive way to increase both HW and spectral efficiency which are the primary concerns that need to be addressed when refarming to LTE/WCDMA.

12.3.8 Signaling Improvements

Advanced techniques that allow GSM traffic and signaling channels to operate in a squeezed (narrowband) spectrum are essential to ensure the proper operation of a GSM-installed base in the case of GSM spectrum refarming for LTE needs.

Originally, in the 3GPP standard, the robustness of the signaling FACCH and the SACCH channels was designed to match the error protection schemes of the standard codecs (full rate, half-rate and enhanced full rate). With the introduction of AMR speech codecs, the robustness of the traffic channels has been considerably improved. The most robust AMR codec modes that is, AFS 4.75, AFS 5.9 provide sufficient voice quality even at very low C/I levels. However, signaling has not been improved by AMR and therefore SACCH and FACCH protection schemes cannot cope with the same C/I conditions as AMR codecs. Thus, with the usual call drop indication mechanisms, applied in AMR networks, calls may be indicated as “dropped” from a signaling point of view, although speech communication is still possible with an acceptable quality. This is especially important for spectrum refarming where the GSM network operates in a narrowband scenario, where typically lower C/I conditions are met and it is crucial to adjust signaling robustness to the AMR capabilities.

There are several proprietary solutions to adjust the signaling performance to AMR capabilities. Additionally changes to 3GPP GERAN standard have been introduced to improve the error protection schemes for FACCH and SACCH. “Repeated Downlink FACCH” and “Repeated SACCH” have been defined in the 3GPP GERAN specification TS 44.006 [8] for a Release 6-compliant MS that is capable of performing joint decoding of two successively repeated FACCH/SACCH blocks. The MS indicates the support of these features via the MS Classmark 3 Information Element called Repeated ACCH, as defined in 3GPP TS 24.008 [9]. The repeated DL FACCH/SACCH procedure foresees a serial repetition of the FACCH

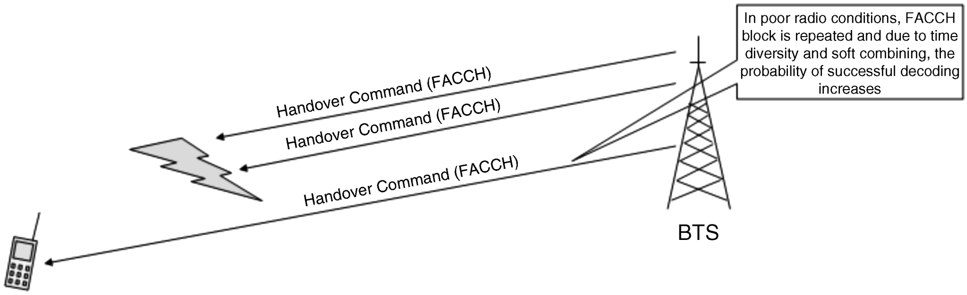
In poor radio conditions, FACCH block is repeated and due to time diversity and soft combining, the probability of successful decoding increases
Handover Command (FACCH)
Handover Command (FACCH)
Handover Command (FACCH)
BTS

Figure 12.30 Repeated FACCH procedure.

SACCH blocks. The MS can then enhance its link performance by attempting soft decision combining of the repeated FACCH/SACCH blocks. According to link-level simulation results, the expected gain in decoding performance is about 3dB (for legacy MS) to 5 dB (for Release 6 MS that performs soft combining). This link-level improvement reduces the number of lost FACCH/SACCH blocks and hence decreases the number of dropped calls due to radio link failure or handover failure.

Repeated FACCH is based on the principle that when repeated FACCH blocks are combined in the receiver, a decoding gain is achieved, thanks to the time diversity between the transmissions.

With the Repeated Downlink FACCH (Figure 12.30), the duplicate FACCH frame is sent using the speech codec's tolerance for the stolen speech frames (for signaling purposes). These stolen speech frames can be used by the receiving end to provide a second chance for successful decoding. The network may retransmit the FACCH block 8 TDMA frames after sending the original FACCH block (or 9 TDMA frames, if an idle frame or a SACCH occurs in between). If the mobile receives both FACCH blocks but is unable to decode either of them independently, then it attempts the joint decoding of two blocks (if MS is Release 6-compliant). With a legacy MS, soft combining is not possible but diversity gain is achieved when the legacy mobile attempts to decode both FACCH frames independently.

The Repeated SACCH, like the Repeated Downlink FACCH, makes use of the time diversity between repeated transmissions to increase the likelihood of a successful decoding. For SACCH reception on the downlink, the MS attempts to decode a single SACCH block first (without attempting to combine it with the previously received block). If decoding fails, the mobile requests the SACCH repetition. In the next SACCH frame, the mobile will attempt decoding, after combining it with the previously received SACCH frame. For SACCH retransmission, in the uplink, MS first checks if Repeated SACCH is ordered by the network (by checking the flag in the last DL SACCH block) and if that previous SACCH block has not already been retransmitted. The mobile then transmits a duplicate frame instead of the originally scheduled frame (Figure 12.31).

To adjust the signaling performance to AMR capabilities, wireless network equipment providers have developed several proprietary solutions. Among these solutions, there is an option to reflect the different robustness of AMR against interference in separate settings for Radio Link Timeout for AMR and non-AMR calls. The aim of the Radio Link Timeout (RLT) is to force the release of the call when the speech quality is so poor that the majority of subscribers would have manually released the call anyway. Considering that AMR calls are

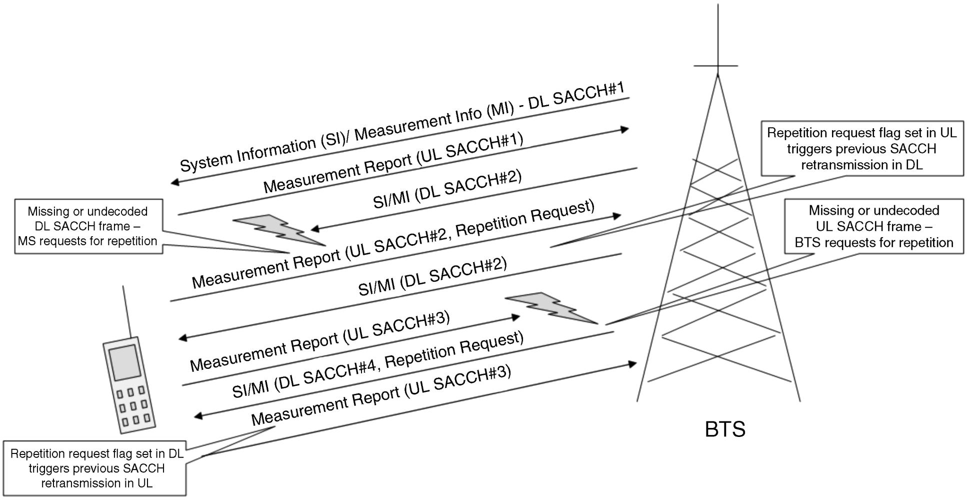
System Information (SI)/ Measurement Info (MI) - DL SACCH#1
Measurement Report (UL SACCH#1)
SI/MI (DL SACCH#2)
Missing or undecoded DL SACCH frame – MS requests for repetition
Measurement Report (UL SACCH#2, Repetition Request)
SI/MI (DL SACCH#2)
Repetition request flag set in UL triggers previous SACCH retransmission in DL
Missing or undecoded UL SACCH frame – BTS requests for repetition
Measurement Report (UL SACCH#3)
SI/MI (DL SACCH#4, Repetition Request)
Measurement Report (UL SACCH#3)
Repetition request flag set in DL triggers previous SACCH retransmission in UL
BTS

Figure 12.31 Repeated SACCH procedure.

more robust than EFR calls, the common RLT value for AMR and non-AMR calls may cause the AMR calls to be unnecessarily dropped from a signaling perspective (while the speech quality is still at acceptable level). For this reason, separate RLT thresholds for AMR and non-AMR calls have been implemented. The RLT threshold for AMR should be at a much higher value than for EFR. Trials in a real network proved that an RLT increase (e.g., from 20 for EFR to 32 for AMR), significantly reduces call drops while maintaining the speech quality at the acceptable level.

Next, proprietary techniques to fine tune signaling performance to AMR capabilities are achieved by improving the C/I for the signaling channels by applying a temporarily higher DL transmit power on FACCH and SACCH bursts. It was found that a 3 dB improvement in C/I, offered by Repeated FACCH for the handsets complied with Release 5 and earlier, is not enough to give a reliable operation with the most robust AMR FR codec. Therefore, for legacy mobiles, the FACCH/SACCH Power Increment feature is used and temporary increments transmit power on signaling channels above the level ordered by the power control procedure. Power Increment is a practical and fully backwards compatible option to improve the probability of successful decoding of the FACCH/SACCH frames. Under normal radio conditions, both FACCH and SACCH are transmitted using the power commanded by the power control algorithm for the traffic channel. In poor radio conditions, however, based on a proprietary trigger mechanism (e.g., RxQual based, FACCH repetition based or MS codec request based), FACCH and SACCH are transmitted independently of each other with power incremented by, for example, 2 dB in relation to the currently used TCH transmit power commanded by the power control. To avoid the undesired effect of permanent overpower on the interference level experienced on TCH channels, power increment on FACCH and SACCH is applied only if the radio conditions degrade below a certain quality threshold, or FACCH repetition is required or MS requests the lowest downlink codec (which indicates poor radio conditions).

Another proprietary solution used to adjust the signaling performance to AMR robustness is the reduction of the handover (HO) signaling message length. Handover Command (that is used in the intercell HO) and Assignment Command (sent in intracell HO) are the longest messages in the handover procedures and therefore affect handover performance the most. The longer these messages are, the more FACCH blocks are required to convey them over the radio interface. The greater number of FACCH blocks required for Handover/Assignment Command transmission, the greater chance that one of these FACCH blocks will be lost and finally MS will not be able to decode this message. By minimizing the message length, the performance of the signaling transactions is more reliable, which improves the HO success rate and the overall call drop rate.

Handover/Assignment Command message length reduction is achieved by BSC manufacturers by removing Information Elements (IEs) which are redundant and optional in the given scenario. For example, if Cell Channel Description Information Element is not present, the MS uses the same hopping frequency allocation as in the old cell. This allows BSC to remove 17 octets from the Handover/Assignment Command, thus reducing the number of FACCH blocks for Handover/Assignment Command transmission by 1 FACCH block, effectively improving the performance in terms of HO success rate and call drop rate.

12.4 Migration from TDD Networks

The rapid development of 4G broadband mobile access opens new opportunities for wireless operators. The ones who have already invested in WiMAX or TD-SCDMA could also benefit from LTE. Operators need to address the following questions: how far investments in the old technology can be re-used and how to gradually migrate their existing networks to LTE. The additional challenge is that both technologies will exist in parallel during the migration period and certain countermeasures need to be taken to avoid harmful interactions.

WiMAX technology is deployed worldwide; hence its migration process is described in detail in other chapters. TD-SCDMA specifics are also covered.

12.4.1 WiMAX

WiMAX stands for Worldwide Interoperability for Microwave Access. The technology was developed to provide high speed data rates for fixed stations. WiMAX is covered by the family of IEEE 802.16 standards, where the most advanced solution is 802.16m (also called WiMAX 2). However, this standard is not yet widely deployed, therefore the more common version 802.16e will be discussed here.

Fixed WiMAX specifies various channel sizes, among them 5 MHz, 7 MHz and 10 MHz are mostly used. Duplex technology foresees both FDD and TDD, however, all currently operating networks use TDD as the main option. Bandwidth and the spectrum of WiMAX are closely connected, depicted in Table 12.7:

Table 12.7 WiMAX spectrum allocation.

Spectrum [GHz]	WiMAX bandwidth [MHz]
2.3–2.4	5, 10
2.496–2.690	5, 10
3.3–3.4	5, 7, 10
3.4–3.8	5, 7, 10

TD-LTE technology is the logical choice for WiMAX migration not only due to its TDD nature but also due to frequency band allocation. Keeping in mind the current TD-LTE hardware availability, one can note that 3GPP band 40 (2.3 GHz) and 41 (2.6 GHz) are the most suitable candidates. Bands above 3 GHz are just being standardized for TD-LTE and they are still rarely used (e.g., band 42) as opposed to B40 and B41.

12.4.1.1 Migration Strategy

Selection of the most appropriate migration strategy is strictly related to the customer spectrum resources. The first assumption is that TD-LTE will be operating in the frequency block migrated from WiMAX carrier.

When an operator's spectrum is substantially limited (e.g., single 5 MHz WiMAX carrier), the whole existing WiMAX radio network must be refarmed into LTE within a selected geographical region. It is not very likely that the whole network will be migrated during single maintenance window–there will be regions migrated to TD-LTE and the ones with WiMAX. Consequently, at the technology border, inter-system interference is expected and an operator has to take countermeasures to avoid harmful interactions.

Another case is when an operator's spectrum resources are sufficient to operate both WiMAX and LTE system concurrently. WiMAX resources have to be partially converted either by reduction of WiMAX carriers in operation or by WiMAX sparse reuse tightening (e.g., re-use of 1x3 is tightened into $N = 1$ frequency re-use). Note that WiMAX resources reduction does not bring service quality degradation. A certain amount of subscribers will be served by LTE, whereas the remaining users can still be served by the narrowed WiMAX resources. This mode of operation yields strict requirements for inter-system's interference and their mutual isolation as both systems operate in adjacent bands. When LTE traffic grows, further WiMAX carriers could be migrated.

The last option refers to the case when an operator is resistant to replacing its WiMAX environment and decides to build a separate greenfield LTE network as an overlay to the legacy technology by acquiring additional spectrum resources. As WiMAX traffic decreases, further pieces of spectrum can be reassigned to LTE. This kind of scenario is rather academic since spectrum resources are scarce.

12.4.1.2 Coexistence of Systems

As outlined in Chapter 11, each migration option includes a scenario where both systems operate concurrently. This happens either by sharing co-located sites in spectrum-rich options or at the LTE–WiMAX systems border.

Co-located BTSs operate in close proximity, hence the most likely interaction is that transmitter of one system BTS affects another system's receiver. When systems are not co-located but operate over the same area, also BTS–UE interference scenarios are possible.

In TDD, transmission and reception occur at different time intervals. Sufficient inter-system isolation becomes an issue when RX and TX periods of interferer and victim overlap. This kind of operation is referred as unsynchronized networks. When systems are unsynchronized, certain isolation requirements have to be guaranteed to avoid quality degradation. Since TD-LTE is a new system with a variety of configuration options and features, it is expected that it will be aligned to minimize its impact on the existing environment.

The first step is to select a TD-LTE frame configuration which matches the DL and UL periods with the operating WiMAX frame. The second is to use common synchronization reference signal and fixed delays to minimize overlapping periods of UL/DL transmission from both systems. Such steps are referred as time-domain systems synchronization.

The minimum inter-system isolation is derived from the maximum allowed interferer signal level which is specified by the 3GPP/WiMAX standards. Out of band emission, selectivity and blocking requirements need to be carefully verified to harmonize the systems.

When co-located TD-LTE and WiMAX BTSs are unsynchronized and operate in the same band, they may require up to 115 dB of isolation, while for different bands operation system isolation is relaxed to 79 dB.

Typically, co-located systems isolation is achieved by the appropriate antenna allocation when dedicated antenna systems are used. A shared antenna system usually is built by means of a combiner, and there is the possibility to provide sufficient isolation. Another option is to deploy a dedicated filter which cuts off the adjacent channel signal coming from the other system components. Nevertheless, with typical antenna separation or filtering, we can expect up to 50–60 dB of isolation and 115 dB is difficult to attain.

12.4.1.3 Co-Located Systems

Among many options, the synchronization of TDD systems is the best choice for co-located systems. The synchronization in this context refers to the case where there is strict coordination between the UL and DL periods of both technologies. When systems are synchronized, UL/DL isolation is provided in the time domain. Hence other countermeasures such as antenna separation, filtering or separation in frequency domain by guard band can then be relaxed. The difficulty is that usually interacting systems cannot be perfectly aligned and additional techniques have to be also used to avoid system quality degradation.

As the first step, the newly introduced TD-LTE system has to be aligned with the existing WiMAX frame. The WiMAX TDD frame duration is 5 ms, which matches the switching period for TD-LTE frame configurations 1 and 2 (Figure 12.32). In total, there are 47 OFDM symbols (102.86 μs) per 5 ms frame for 5 and 10 MHz WiMAX bandwidth (which are foreseen for bands B40 and B41). The 47 symbols are split into UL and DL according to the predefined

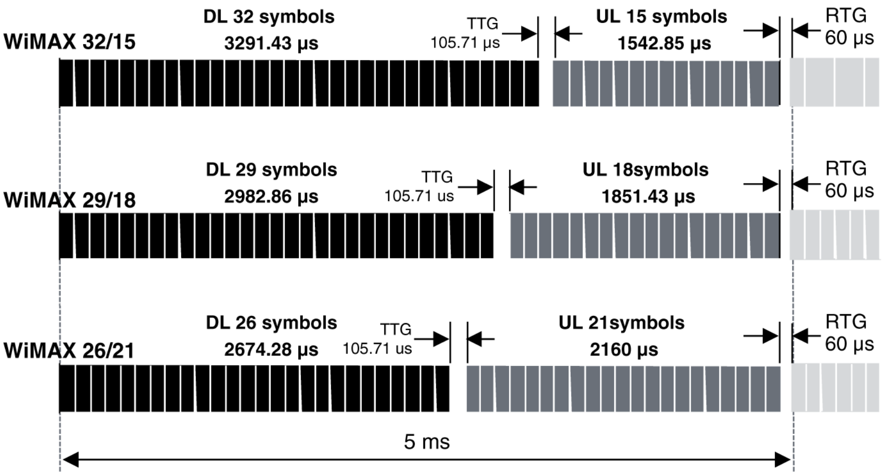

Figure 12.32 WiMAX frame configuration examples.

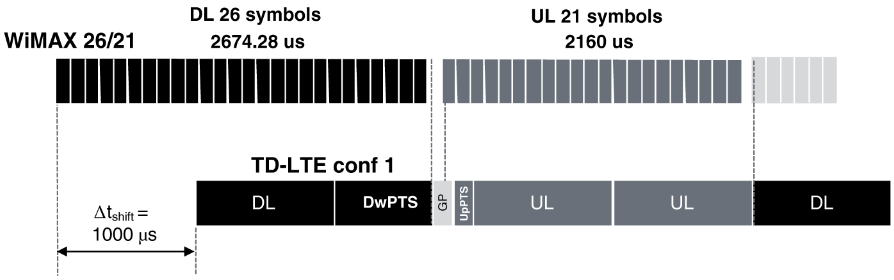

Figure 12.33 WiMAX frame 26/21 coexistence with TD-LTE frame configuration 1.

schemes. Currently commonly used DL/UL shares are 32/15, 29/18 and 26/21. This notation stands for the number of symbols used in each corresponding direction. Another naming convention is to use the percentage of the total symbols amount (e.g., 67/33, 60/40 and 55/45 and 55/45 correspondingly).

The DL and UL periods are separated by a transmit-to-receive transition gap (TTG with 105.71 μs duration) which has the same role as Guard Period (GP) for TD-LTE. The UL/DL switch is separated by the receive-to-transmit transition gap (RTG) with 60 μs duration.

The selection of the complementary TD-LTE frame configurations takes into account the corresponding UL and DL periods of WiMAX. For the LTE frame type 2 (TDD), configurations 1 and 2 give an approximate match to the WiMAX frame parameters. The whole 10 ms TD-LTE frame consists of two 5 ms half-frames with the same structure, for the sake of simplicity, half-frame relations will be discussed further. Note that frames have to be delayed to attain TDD synchronization. Exact delay comes from the comparison of DL/UL periods and switching points; usually the instance of frame start is relative to GPS 1 pps, or another time standard used for the overall TDD system synchronization.

In the first example (Figure 12.33), the WiMAX frame 26/21 is shown. Selection of the appropriate TD-LTE frame is biased by WiMAX UL period. The TD-LTE frame configuration 1 with two UL subframes, having a total duration of 2 ms is nearest to the 2160 μs of WiMAX UL share. TD-LTE frame delay is selected in a way that UL/DL switching points of both systems are as close as possible in the time domain.

Alignment between the beginning of the subsequent WiMAX frame and the end of the second TD-LTE UL subframe requires a delay of TD-LTE system by approximately 1000 μs. Aligned frames do not overlap with each other and moreover there is a guard period from GP/TTG overlap providing separation between systems (which will be discussed further). Note that for a special subframe configurations (SSC) with an extremely short GP, it might be difficult to obtain sufficient separation. The light-gray period at the end of the WiMAX frame corresponds to the DL of subsequent frame.

The second scenario (Figure 12.34) is for WiMAX frame 26/21. Again, TD-LTE frame configuration 1 fits to the 1851.43 μs of WiMAX UL share. Alignment of UL/DL parts is not trivial here since WiMAX UL share is less than 2 ms and for all the cases partial overlap of UL and DL frames will occur. The trade-off is when the TD-LTE system is delayed by approximately 1051 μs, the Uplink Pilot Timeslot (UpPTS) period will be impacted by WiMAX DL and the last symbol of second UL subframe will interfere with the DL of the subsequent WiMAX frame. Lower delay value would affect also the beginning of the first UL subframe, while more delay would spoil the subsequent symbols of the second UL

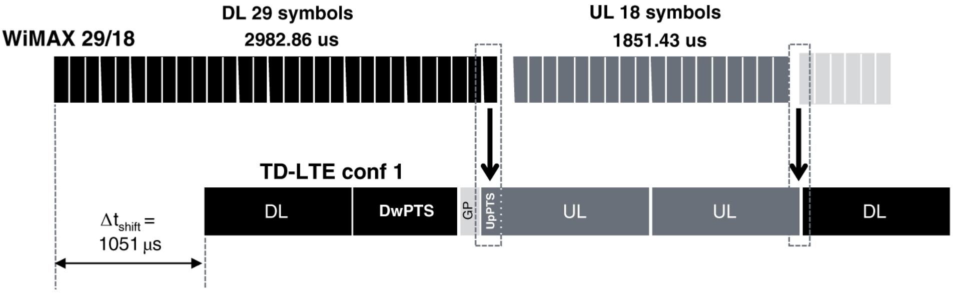
WiMAX 29/18
DL 29 symbols
2982.86 us
UL 18 symbols
1851.43 us
TD-LTE conf 1
DL
DwPTS
GP
UpPTS
UL
UL
DL
Δt_{shift} =
1051 μs

Figure 12.34 WiMAX frame 29/18 coexistence with TD-LTE frame configuration 1.

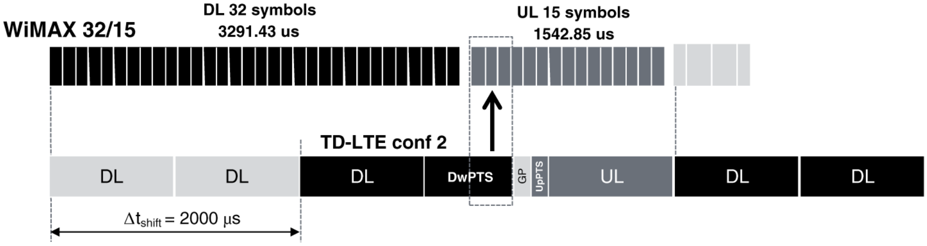
WiMAX 32/15
DL 32 symbols
3291.43 us
UL 15 symbols
1542.85 us
TD-LTE conf 2
DL
DL
DL
DwPTS
GP
UpPTS
UL
DL
DL
Δt_{shift} = 2000 μs

Figure 12.35 WiMAX frame 32/15 coexistence with TD-LTE frame configuration 2.

subframe. Nevertheless the assumption that the old system remains unaffected is maintained, since the TD-LTE does not interact with WiMAX.

The last scenario, Figure 12.35 covers the case when the 32/15 WiMAX frame is used. The TD-LTE frame configuration 1 is no longer suitable, since with the short WiMAX UL share of 1500 μs duration, the TD-LTE UL will be significantly affected. This explains why the TD-LTE frame configuration 2 has to be selected here. When the beginning of the subsequent WiMAX frame is aligned with the end of the TD-LTE UL subframe, the delay of 2000 μs will have to be applied to the TD-LTE frame. With such configuration a part of the WiMAX UL will be heavily interfered with by the Downlink Pilot Timeslot of TD-LTE. Consequently significant UL degradation for WiMAX can be expected.

12.4.1.4 TD-LTE – WiMAX Coexistence Features

For the scenarios where TD-LTE interfere with coexisting WiMAX, dedicated features have been developed to mitigate the impact. Taking the example of WiMAX 29/18 scenario, one can see that TD-LTE is affected during the UpPTS period and the last symbol of TD-LTE subframe #3 and #8.

The first problem can be solved by UpPTS blanking (Figure 12.36). The principle of this functionality is to switch off the TD-LTE eNB receiver during UpPTS and to start reception from the first UL subframe. Additionally there is no UL scheduling during UpPTS, that is, the Sounding Reference Symbols (SRS) and PRACH 4 configuration are disabled in UpPTS. To maintain the system's functionality, the UpPTS content (mainly SRS) is moved to the last symbol of the UL subframe. What has to be emphasized is that LTE standard already foresees

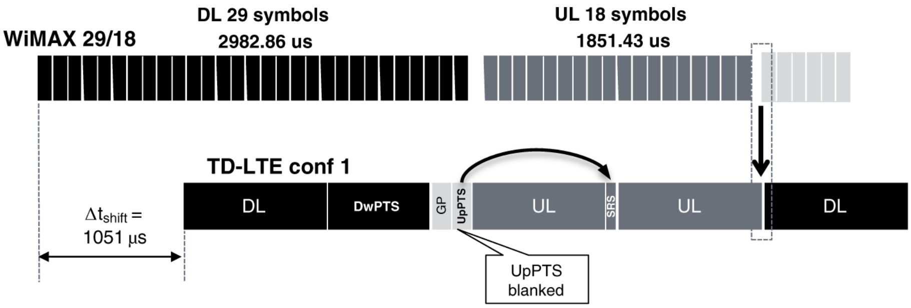
WiMAX 29/18
DL 29 symbols
2982.86 us
UL 18 symbols
1851.43 us
TD-LTE conf 1
Δt_{shift} =
1051 µs
DL
DwPTS
GP
UpPTS
UL
SRS
UL
DL
UpPTS
blanked

Figure 12.36 UpPTS blanking feature.

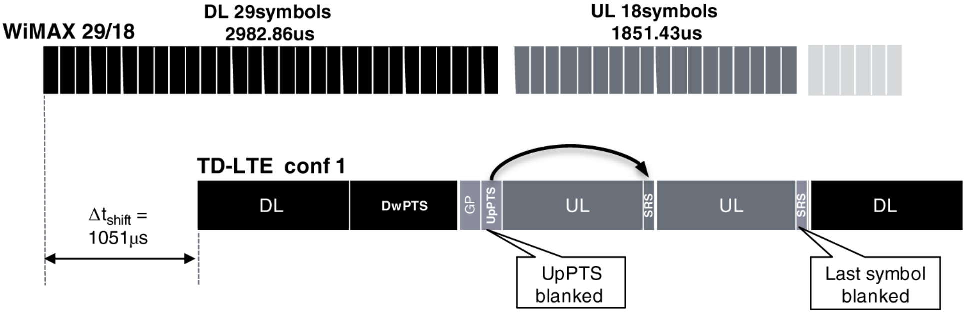
WiMAX 29/18
DL 29symbols
2982.86us
UL 18symbols
1851.43us
TD-LTE conf 1
Δt_{shift} =
1051µs
DL
DwPTS
GP
UpPTS
UL
SRS
UL
SRS
DL
UpPTS
blanked
Last symbol
blanked

Figure 12.37 UpPTS and last symbol of UL subframe #3 blanked.

the possibility of SRSs allocation in UL subframes. Consequently, it means that such a solution is transparent to the UE and requires only modifications of the eNB software to avoid scheduling during UpPTS. When blanking is activated, the GP is virtually extended by UpPTS. One has to be aware that SRS uses a single symbol of the UL subframe, therefore the PUSCH capacity will be slightly reduced and moreover a shortened PUCCH format will have to be used.

Bearing in mind that the standard reserves UpPTS and the last symbol of the UL subframes for SRS use, one can easily note that the same approach can be repeated to avoid interference during the second UL subframe. What needs to be done is to reserve UL resources during the last symbol of the UL subframe #3 (the first half-frame) and #8 (the second half-frame) but UE-specific SRS will not be scheduled in subframe #8 (Figure 12.37). Again, this feature is transparent to the UE and requires only modification of the eNB software. It is recommended to activate this feature together with UpPTS blanking.

12.4.1.5 TDD Distance Protection Limits

In general, TDD systems have to take into account that there is a various propagation delay during transmission from mobile stations. The system design has to guarantee that the transmission from the mobile located anywhere in the cell appears at the BTS receiver exactly when the uplink reception is started. That is why WiMAX and TD-LTE both have reserved a certain amount of time between transmission and reception at the BTS, which allows a distant mobile transmission to arrive just before the BTS start its reception. Such periods are known as GP for TD-LTE and TTG for WiMAX. Guards/Gaps at BTS are fixed, while the mobile stations have to individually adjust their timing depending on their position within the cell. The mobiles at the cell edge have no additional delay to be applied, since for them the propagation delay is equal to the GP or TTG. On the other hand, the mobiles close to the BTS have to wait with their transmission since their propagation delay is low. This mechanism is known as Timing Advance and the duration of the guard periods at BTS defines the maximum cell range. Another effect is that during guard period there is no reception, thus the system is resistant to any unwanted transmission that might arrive at the BTS during this period.

It is obvious that such a guard period is applicable only up to certain propagation delay limits. Typically the signals from distant BTSs are at low levels due to terrain morphology and buildings shadowing, therefore they are not considered an interference source. However, for reflected paths, the propagation delay can be sufficient to affect the system even at close distances. Problems can also be expected for elevated sites with long line-of-sight transmission to the distant victim BTSs. Even if it seems to be counterintuitive, the solution is to allocate the interacting BTSs closer so that the propagation delay is lower and the guard period will protect the receiver from such interference.

When interacting networks are synchronized, the maximum distance between BTSs where the UL reception is still guarded can be derived (Figure 12.38). Note that an analysis has to be

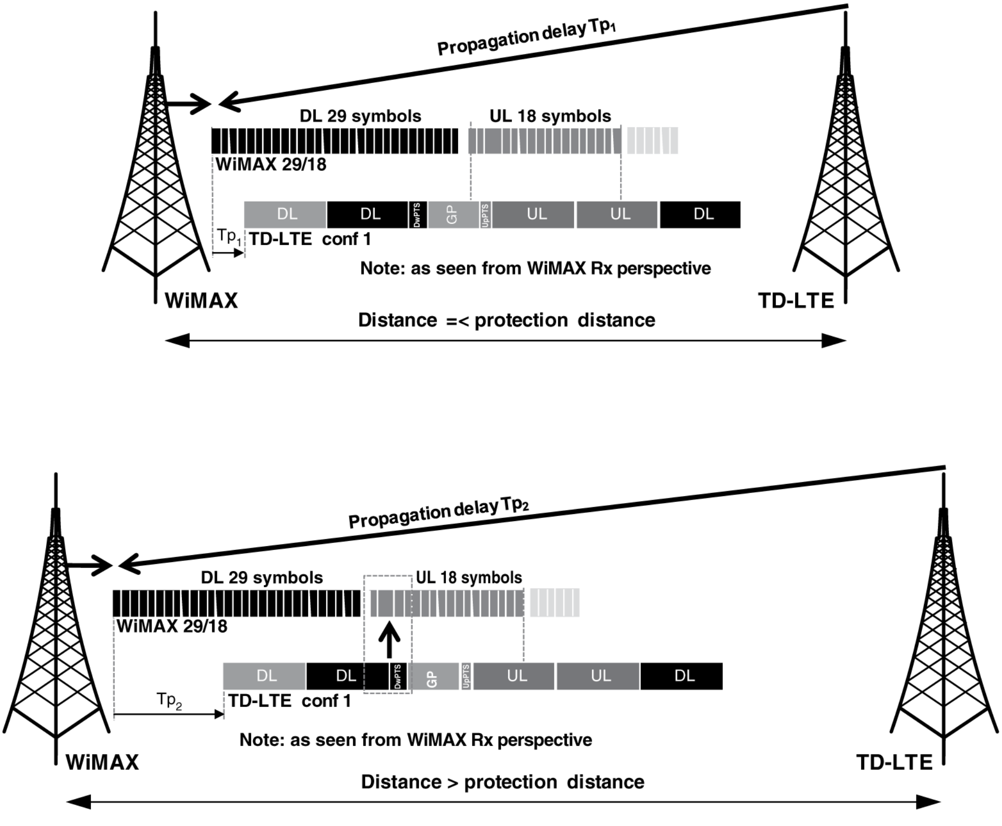
Propagation delay Tp_1
DL 29 symbols
UL 18 symbols
WiMAX 29/18
DL
DL
DwPTS
GP
UpPTS
UL
UL
DL
Tp_1
TD-LTE conf 1
Note: as seen from WiMAX Rx perspective
WiMAX
TD-LTE
Distance =< protection distance
Propagation delay Tp_2
DL 29 symbols
UL 18 symbols
WiMAX 29/18
DL
DL
DwPTS
GP
UpPTS
UL
UL
DL
Tp_2
TD-LTE conf 1
Note: as seen from WiMAX Rx perspective
WiMAX
TD-LTE
Distance > protection distance

Figure 12.38 Propagation delay and protection distance relations.

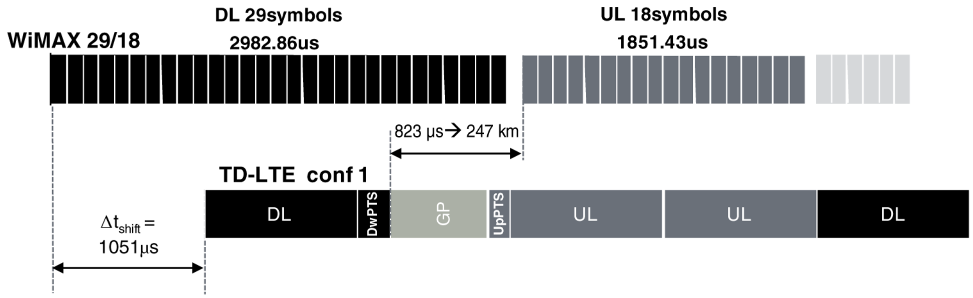

Figure 12.39 WiMAX protection distance for WiMAX frame configuration 29/18 and TD-LTE Special Subframe Configuration 5.

done from the affected BTS receiver's point of view, for example, exactly at the receiver location to consider the frames' timings and the offender transmission delay due to propagation. The TD-LTE standard defines several Special Subframe configurations with predefined guard periods. The maximum cell ranges and protection distances depend on which configuration is selected. When the propagation delay exceeds the limits given by the Guard Periods, an additional isolation is required, similar to the case of non-synchronized systems.

The analysis of the maximum separation distance for co-existing systems assumes that systems are synchronized and an appropriate time delay is applied for TD-LTE. When systems are co-located, the synchronization helps to avoid any interactions, however, as several BTSs are located within a coverage area, the victim BTS receives interference from these sites. As systems are synchronized, the start instance of each frame is known, so a propagation delay component can easily be estimated.

In the example (Figure 12.39), the WiMAX 29/18 coexistence with TD-LTE frame configuration 1 and SSC 5 (where GP is equal to 642.71 μs) is shown. When TD-LTE is the aggressor and WiMAX is the victim, the maximum protection time can be evaluated for synchronized frames as the period from the end of DwPTS to the start of WiMAX UL symbol when the WiMAX reception starts. In the example it is equal to 823 μs, and this is the minimum time at which delayed TD-LTE frame DL would interfere with WiMAX reception. Keeping in mind that free space delay is approximately 0.3 km per 1 μs, it can easily be recalculated into the separation distance of 247 km. It is not very likely that the delayed transmission will have enough power due to propagation loss over such a long distance, so it is assumed that WiMAX will not be impacted by the TD-LTE in that scenario.

Interference relations are mutual; hence, the impact at the TD-LTE receiver will be also evaluated (Figure 12.40). The synchronized WiMAX frame will interfere with the TD-LTE reception even without any propagation delay. The only option to avoid interference and to gain any separation period is to blank UpPTS. Even when this is done, the TD-LTE would start to be affected as soon as the delay reaches 68.1 μs. This corresponds to the separation distance of 20 km. Please note that this is the actual limit for systems interaction, and it does not depend on the TD-LTE special subframe configurations and its GP.

12.4.2 TD-SCDMA

TD-SCDMA stands for Time Division Synchronous Code Division Multiple Access and it is also known as UTRA TDD 1.28 Mbps. The standard was developed as an alternative to

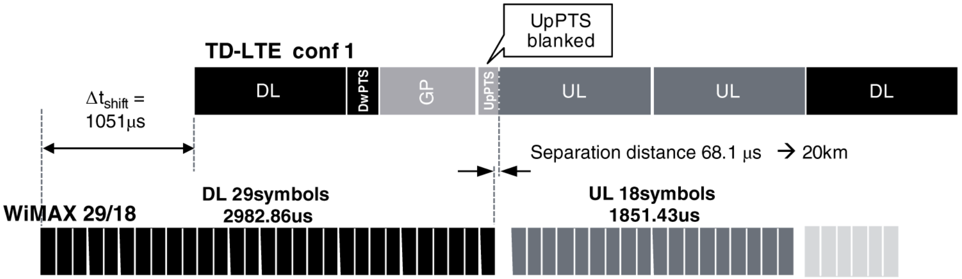
UpPTS blanked
TD-LTE conf 1
Δt_{shift} = 1051µs
DL
DwPTS
GP
UpPTS
UL
UL
DL
Separation distance 68.1 µs → 20km
WiMAX 29/18
DL 29symbols 2982.86us
UL 18symbols 1851.43us

Figure 12.40 TD-LTE protection distance for WiMAX frame configuration 29/18 and TD-LTE Special Subframe Configuration 5.

WCDMA in China by the Chinese Academy of Telecommunications Technology (CATT), Datang Telecom, and Siemens AG. The system is mainly deployed in China with country-wide service coverage.

TD-SCDMA uses TDD duplex separation, and similar to WiMAX, it has an option of adjusting the number of timeslots used for DL and UL for different data rate requirements. The standard has been adopted by 3GPP since Release 4 and it is known as “UTRA TDD 1.28 mbps Option.” Even if it is the 3GPP system, its migration strategy is described here as its deployment is restricted to the selected geographical areas. Due to its specifics, additional aspects have to be considered for co-existence scenarios, in opposition to the worldwide deployment of WCDMA.

The TD-SCDMA radio frame has a duration of 10 ms and it is subdivided into two subframes of 5 ms each (Figure 12.41). Each subframe is composed of seven regular time slots (TS) and a special time slot. The TS duration is 675 µs (6400 chips). The TD-SCDMA special time slot consists of the Downlink Pilot Timeslot (DwPTS, 75 µs), Guard Period (GP, 75 µs) and the Uplink Pilot Timeslot (UpPTS, 125 µs).

The border timeslots TS0 and TS6 are always configured as the downlink direction. TS1 is always allocated as the uplink. The fixed DL/UL switching point is always at the special timeslot GP. TS2–TS5 can be configured flexibly (but contiguous allocation is expected) as UL or DL, hence the second flexible switching point can occur anywhere between the end of TS1 and the end of TS5.

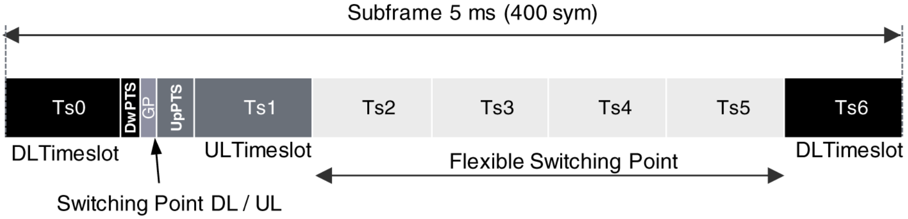
Subframe 5 ms (400 sym)
Ts0
DwPTS
GP
UpPTS
Ts1
Ts2
Ts3
Ts4
Ts5
Ts6
DLTimeslot
ULTimeslot
Flexible Switching Point
DLTimeslot
Switching Point DL / UL

Figure 12.41 TD-SCDMA subframe structure.

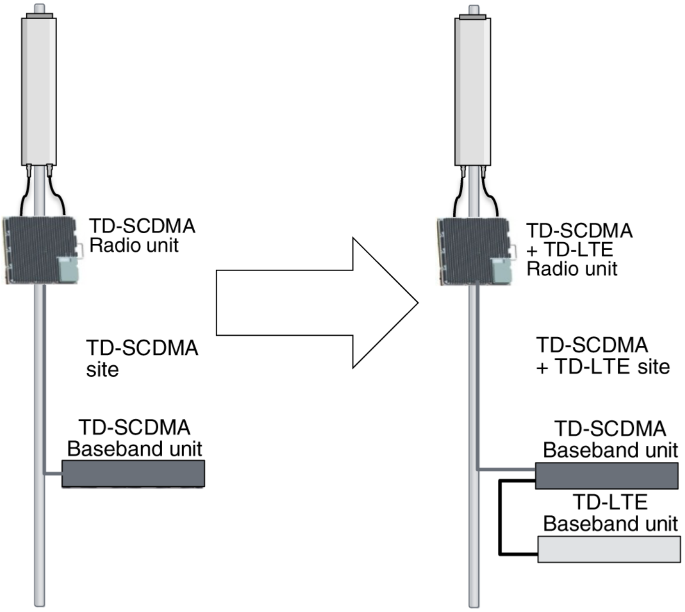

Figure 12.42 TD-SCDMA site migration.

12.4.2.1 TD-SCDMA Migration Strategy

The installed TD-SCDMA base uses 1.9 GHz, 2.0 GHz and 2.3 GHz spectrum, which matches the TD-LTE spectrum allocation for bands B39 (1.9 GHz) and B40 (2.3 GHz).

For the migration strategy (Figure 12.42), the same rules as for WiMAX case apply. The co-existing TD-LTE requires TD-SCDMA spectrum resources to be de-allocated, by the reduction of carriers in operation or an additional spectrum has to be acquired.

The majority of sites use modern software-defined radios, making migration scenarios easier. As the radio is able to generate signals of various radio technologies concurrently, the only point for hardware migration is to provide a TD-LTE baseband in addition to the existing TD-SCDMA unit. What has to be emphasized is that the antenna systems do not require modification.

Coexisting systems impose certain requirements for systems' synchronization. As previously mentioned for WiMAX, the alignment process starts from the appropriate TD-LTE frame selection, and then the frames delay is analyzed to align switching points. Note that synchronization is possible only for the selected TD-SCDMA TD-LTE frame pairs.

As shown in Figure 12.43 for the TD-SCDMA 6DL:1UL frame, even if the UL/DL switching point is aligned, there is still interference during UpPTS of co-existed TD-LTE frame 2. This is also happens for TD-SCDMA frame 3DL:4UL where DwPTS interferes first with TD-SCDMA TS. Such cases have to be treated as an unsynchronized operation and sufficient isolation has to be guaranteed.

A synchronized operation requires a delay of TD-LTE frame. Figure 12.44 shows the example for TD-SCDMA 5DL:2UL frame which can be aligned with TD-LTE frame 2 with SSC 5. Alignment of the flexible switching point requires the TD-SDMA frame to be delayed by 692.97 μs.

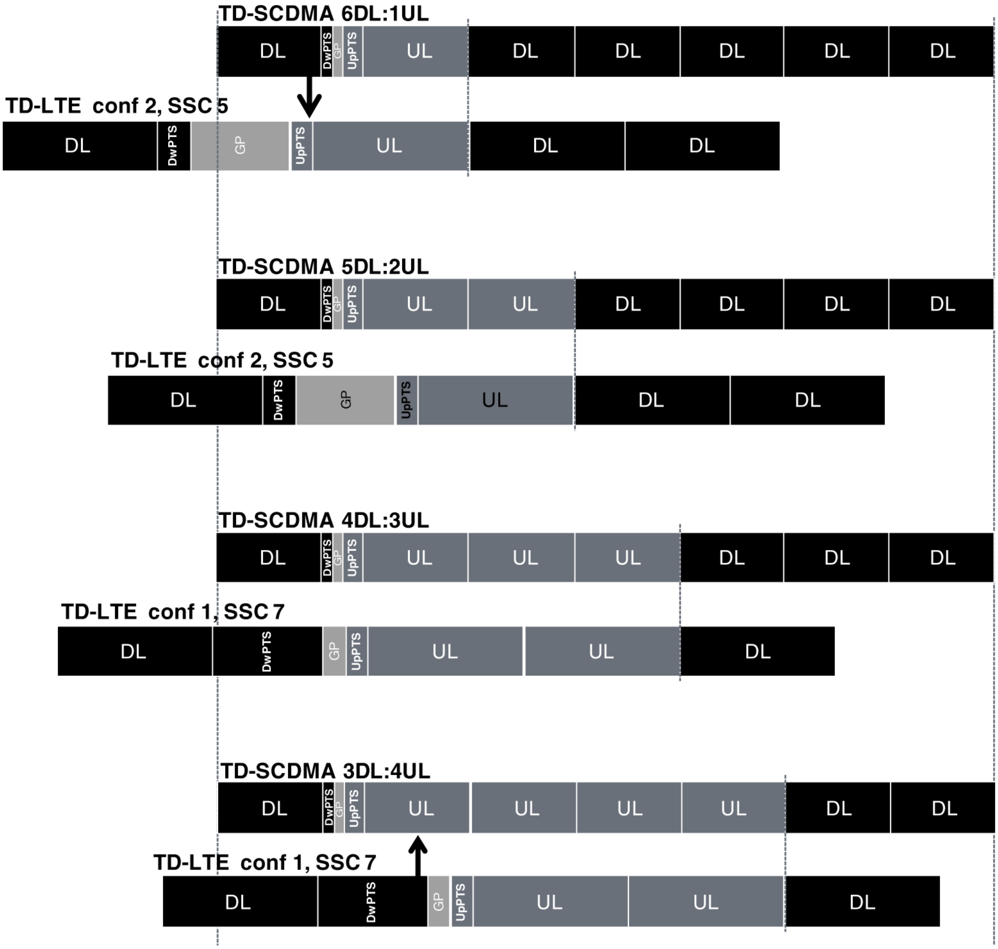
TD-SCDMA 6DL:1UL
DL
DwPTS
GP
UpPTS
UL
TD-LTE conf 2, SSC 5
TD-SCDMA 5DL:2UL
TD-LTE conf 2, SSC 5
TD-SCDMA 4DL:3UL
TD-LTE conf 1, SSC 7
TD-SCDMA 3DL:4UL
TD-LTE conf 1, SSC 7

Figure 12.43 TD-SCDMA and TD-LTE frames alignment.

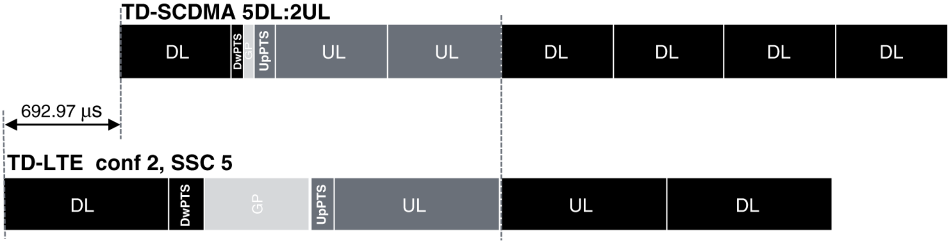
TD-SCDMA 5DL:2UL
DL
DwPTS
GP
UpPTS
UL
692.97 μs
TD-LTE conf 2, SSC 5

Figure 12.44 TD-SCDMA 5DL:2UL aligned with TD-LTE frame 2 SSF5.

12.5 Alternative Network Migration Path (Multi-Operator Case)

Some limited multi-operator network sharing scenarios have been present since the onset of cellular technology, but involved sharing of passive elements that was limited to isolated cases, for example, site sharing at the highest building in town. More advanced sharing was not popular, as the operators considered the network hardware to be their major asset, also the regulators tended to block network sharing. The situation has, however, changed in recent years, and this change in attitude has been caused by several factors:

- Economical downturn, making the operators reluctant to spend money, paired with lowering ARPU.
- No increase in ARPU likely, as the new technologies will principally offer data transfer at flat rates.
- Scarcity of the spectrum to be allocated.
- Need for a wide contiguous frequency band required to achieve high data throughputs that the LTE technology is capable of (due to signaling overhead and lower flexibility of scheduler, the LTE deployments at 1.4 or 3 MHz bandwidth may not achieve satisfactory throughput requirements).
- Technological advances, both in LTE and in legacy radio access technologies, allowing greater flexibility (e.g., carrier aggregation) and high efficiency (e.g., MIMO, EGPRS-2).
- Expected explosion of traffic (several orders of magnitude), calling for investments to be able to handle the traffic in the years to come.
- Cost-cutting measures, calling for outsourcing some of the part of MNO's (Mobile Network Operator) CAPEX and OPEX.
- New business models coming onto the market (managed services offered by the mobile equipment manufacturers, third-party companies to own and manage networks).
- Extremely rapid development of the subscribers' base in the developing countries, with specific constraints of extremely low ARPU and high cost to reach subscribers (lack of power grid, costly backhaul, etc.).
- "Green" becoming word of the day, causing pressure on operators to limit their environmental footprint.

The site's CAPEX and OPEX contribute significantly to mobile operators' expenses, so quite naturally the operators are eager to seek some savings there. Additionally, the LTE is designed in such a way that facilitates the network sharing (all-IP, flexible spectrum, flexible frequency band, carrier aggregation), and the network sharing mechanisms have been in-built into standards since the beginning. Due to the scarcity of the continuous frequency resources, it may happen that the common frequency network sharing methods will be the actual enablers of LTE technology, allowing the operators not only to achieve satisfactory levels of LTE services (i.e., having deployed the LTE over at least 5 MHz band, ideally 10 or 20 MHz), but also to be able to use concurrently LTE and GSM technologies. Figure 12.45 depicts a situation where two operators can benefit from network sharing scenario. The described case relates to the 900 MHz band, and assumes an uncoordinated scenario (i.e., the existing sites will not be re-used by the LTE on a one-to-one basis). Considered is a situation when the spectrum reshuffling is not possible, therefore the operators have no way of rearranging the allocation of sections of spectrum. Operator "B" has two separate parts of spectrum (9 MHz in total), and operator "C" has a contiguous piece 7.4 MHz wide (a third operator, "A," is shown for the sake of

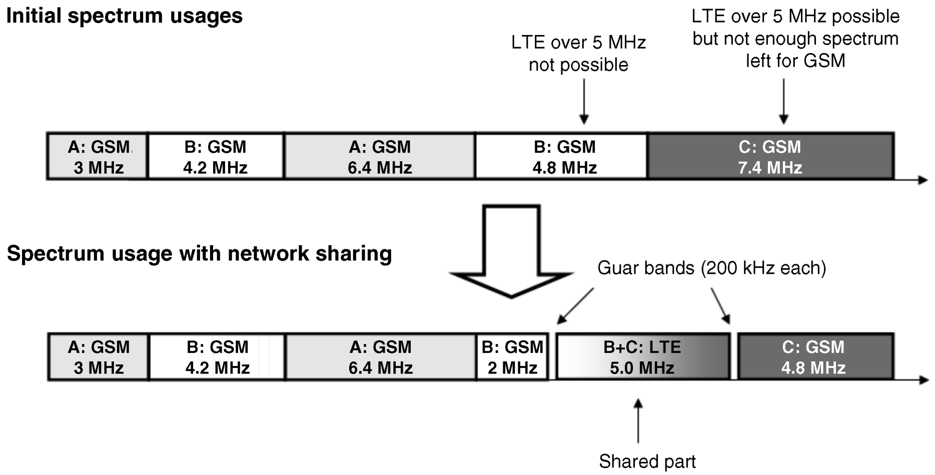
Initial spectrum usages
LTE over 5 MHz not possible
LTE over 5 MHz possible but not enough spectrum left for GSM
A: GSM 3 MHz
B: GSM 4.2 MHz
A: GSM 6.4 MHz
B: GSM 4.8 MHz
C: GSM 7.4 MHz
Spectrum usage with network sharing
Guar bands (200 kHz each)
A: GSM 3 MHz
B: GSM 4.2 MHz
A: GSM 6.4 MHz
B: GSM 2 MHz
B+C: LTE 5.0 MHz
C: GSM 4.8 MHz
Shared part

Figure 12.45 Frequency refarming – enabling 5 MHz LTE and continuation of GSM operation.

completeness). All operators use the spectrum to offer GSM services, but wish to introduce LTE over as wide a band as possible, while continuing to offer GSM. It can be seen that both “B” and “C” are facing the following challenges:

- Operator “B” cannot deploy LTE over 5 MHz bandwidth as it lacks sufficient contiguous frequency resources. The network sharing is in fact the enabler for 5 MHz LTE.
- Operator “C” can deploy 5 MHz LTE, but is left with insufficient resources to continue to offer GSM services (at least in the considered 900 MHz band), as the quality will be compromised.

Note that it was assumed that in order to offer satisfactory GSM services, it is required to have at least 15 channels in BCCH layer (3 MHz wide frequency band) (refer to Section 12.3.5). It is also needed to take into consideration the required guard bands specific for uncoordinated case (as presented in Table 12.4). If both “B” and “C” wish to offer LTE over 5 MHz, they need to have 5.4 MHz of bandwidth, as two 200 kHz-wide slots are needed as guard bands. When a shared band is used for LTE, both operators still have enough bandwidth to offer GSM services. Note, however, that in special cases certain GSM features (e.g., common BCCH) may be needed to assure the satisfactory operation of the GSM network depending on the spectrum arrangement in other bands for example, 1800 MHz – for further details please refer to Section 12.3.

Use of network sharing may be beneficial not only for the operators with insufficient or scattered spectrum to introduce LTE, but also in case of deployment of advanced LTE functionalities such as Carrier Aggregation (CA). Fast implementation of CA gives the operator a competitive advantage over its rivals in a perpetual race to offer higher throughputs to the end users. One of the possible bottlenecks for early introduction of Carrier Aggregation might be the lack of a second carrier or it may happen that the operators’ carriers cannot be paired due to the lack of a proper standard support. To overcome these challenges, operators may build a common LTE network which will be based on the carrier frequencies initially dedicated to each of the participating operators. Upon the introduction of network sharing

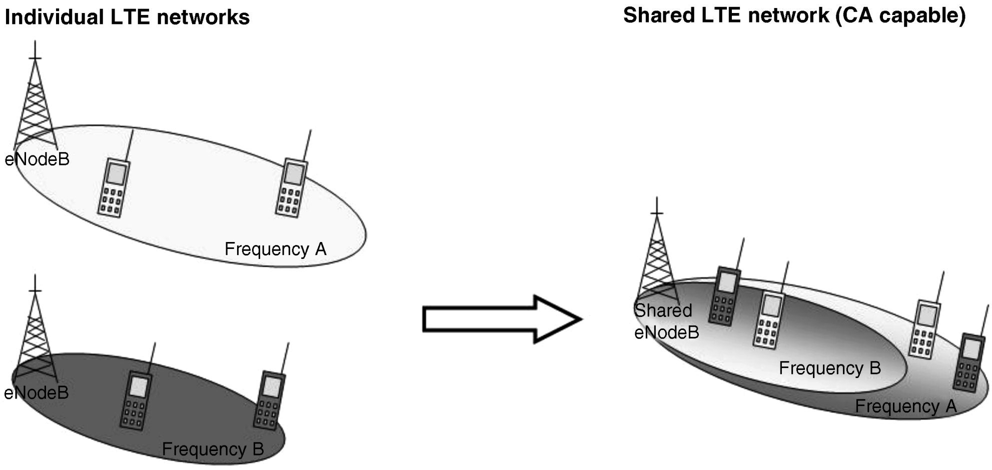

Figure 12.46 Usage of Network Sharing for fast LTE-A deployment.

solutions, for example, MOCN which is described hereafter, users of both operators can utilize resources available in the cells operating on both frequencies. Application of such a scenario allows the operators to benefit not only from resource pooling but also from the frequencies' availability and the reduction of the RAN equipment investment. Moreover, application of network sharing may open opportunities for further expansion of LTE with another carrier, as in the example in Figure 12.46, to increase the competitive advantage of the shared network. Figure 12.46 shows an example of network sharing usage for the introduction of LTE-A features like Carrier Aggregation. Bi-directional associations between cells operating on different frequencies (intra- or inter-band) were assumed to offer CA, regardless of the serving cell frequency.

12.5.1 Introduction to Network Sharing Variants

Network sharing may be done following one of these main principles:

- Participants use individual frequency carriers:
  a. Multi-Operator Base Station Subsystem (MOBSS), solution applicable for GERAN – the BTS equipment and BSC resources are shared.
  b. Multi-Operator Radio Access Network (MORAN), specific for WCDMA and LTE systems – shared is the (e)NodeB equipment and RNC.
- Common frequencies are used by all participants:
  a. RAN-based sharing
    i. Multi-Operator Core Network (MOCN) for GERAN (partial support from 3GPP Release 10, full support from Release 11)
    ii. MOCN for WCDMA (supported from 3GPP Release 6)
    iii. MOCN for LTE (supported from 3GPP Release 8, i.e., as long as LTE exists).
  b. Roaming-based sharing
    i. National roaming.
    ii. Geographical roaming.

Table 12.8 Network-sharing compatibility matrix.

UE 3GPP release	Network sharing method per technology					
	MOBSS (GERAN)	MORAN (WCDMA)	MORAN (LTE)	MOCN (GERAN)	MOCN (WCDMA)	MOCN (LTE)
Below Rel. 99	+	n/a[b]	n/a[b]	+/–[a]	n/a[b]	n/a[b]
Rel. 99, 4 and 5	+	+	n/a[b]	+/–[a]	+/–[a]	n/a[b]
Rel. 6 and 7	+	+	n/a[b]	+/–[a]	+	n/a[b]
Rel. 8, 9 and 10	+	+	+	+/–[a]	+	+
Rel. 11	+	+	+	+	+	+

Notes:
[a] Supports only single PLMN. Support of NITZ and Equivalent PLMN may be required.
[b] WCDMA UMTS starts with Rel.99, LTE starts with Rel. 8.

The virtual operator case (MVNO – Mobile Virtual Network Operator) is excluded from this analysis. There are also other network sharing scenarios, such as, for example, Gateway Core Network where certain core network nodes are shared while the remaining ones are operator-specific [10], regional roaming cases or various other hybrid solutions.

It has to be kept in mind that the network sharing is a complicated and multidimensional issue and many operators might be reluctant to participate in it. Operators may face problems in finding the right partner for various reasons, besides not all such joint ventures will be able to come into existence due to anti-trust laws and regulatory issues. One should not ignore the likely problems in making two different organizations cooperate, but one should also expect many side technological issues: separate tools, different KPIs monitored, different processes (e.g., dealing with site building). An additional issue is the fact that not all UEs may be capable of supporting certain sharing-related features. The detailed compatibility matrix is presented in Table 12.8 ("+" signifies full support, "–" lack of support while "+/–" denotes support with some reservations that are explained in the table notes; "n/a" stands for "not applicable").

12.5.2 MORAN and MOBSS

MORAN/MOBSS functionality allows several operators to share physical radio access nodes, while each participating party owns and maintains their own other elements of mobile network. In particular, the Core Network components are not shared, as presented in Figure 12.47.

The operators sharing the physical equipment continue to use their own licensed frequencies. Because each operator has their dedicated radio resources, they can have their own PLMN identities, carrier frequencies, and Cell ID. The other network parameters can be individual, or common. Each operator's specific end user services are available in the area covered by the shared network. The sharing is fully transparent to the mobile stations, as they see their operators' PLMNs present at the normally used frequency bands. This is further enhanced by the fact that each operator uses its own specific PLMN ID and the UEs continue to display own operator logos. It has to be additionally noted that use of MORAN/MOBSS functionality does not prevent any of the participating operators from simultaneously operating their own dedicated RAN networks. The presence of the MORAN/MOBSS feature requires some modifications in the user plane or control plane message handling. The shared radio access node need to correctly identify the proper message destination for each user. The differentiation is done on the basis of the PLMN on which the given UE has registered itself. Note that the cell

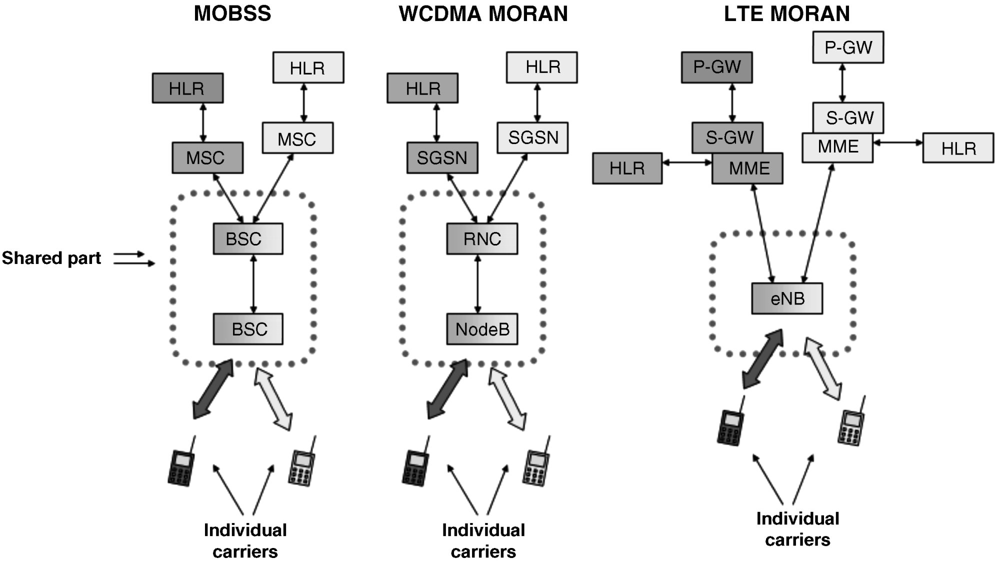

Figure 12.47 MOBSS/MORAN sharing scenario.

identities have to be expressed in CGI (Cell Global Identity) format, to ensure they are unique among operators (a Cell ID is required to be unique only within a single registration area in the given network).

Effectively, in the MORAN/MOBSS solution, the following elements of the network can be shared:

- (e)NodeB (MORAN) or BTS (MOBSS) equipment (baseband resources, battery back-up, air conditioning, etc.);
- backhaul equipment (not necessarily in all cases);
- the site-related elements (buildings, towers, cabinets, antennas, feeders);
- processing capacity in control nodes (RNC, resp. BSC).

Some actions related to the network operation also need to be coordinated between participants: network planning and dimensioning, network roll-out and maintenance, equipment upgrades (software actualization, capacity upgrades). Each of the participants, however, is individually responsible for providing licensed frequencies, providing and operating their own core networks. They should also define and implement their own cell parameters (e.g., cell selection/handover thresholds, neighbor lists), provide their own specific services to the end users. Each of the operators does their own performance and fault monitoring.

The principal benefits of applying MORAN or MOBSS sharing solution are an immediate reduction in equipment cost and OPEX savings. For a greenfield operator, it significantly lowers the costs of entering into the market, as both the volume of the equipment and the commissioning efforts are greatly reduced, as is the time needed to find and acquire the needed sites. An additional advantage is the possibility to conveniently and effectively cover the areas of low traffic. MORAN/MOBSS allows the participating operators to maintain control of their own network traffic in terms of quality and capacity and also does not restrict the operators to

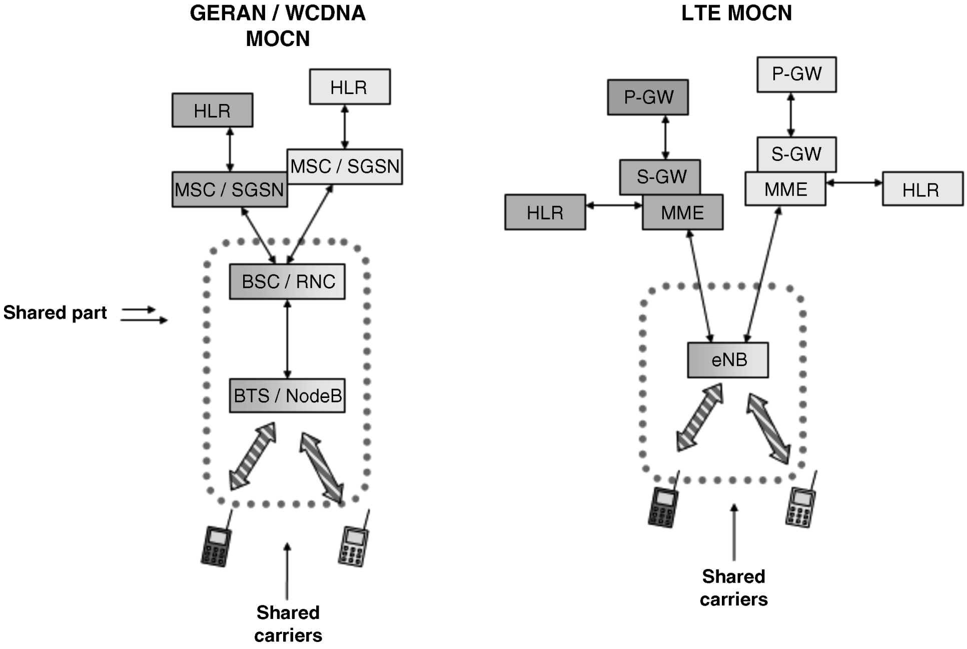

Figure 12.48 MOCN sharing scenario.

signing individual roaming agreements with third parties (thanks to having an individual PLMN ID). It has also to be mentioned that this type of network sharing leaves a secure exit path to their own dedicated radio access equipment for each operator, in the case of traffic volume increase or any unfavorable change of sharing policies by other participants. The additional benefit of MORAN/MOBSS is full support of this solution by all terminals. The actual putting into operation of a MORAN and MOBSS solution may, however, be hindered by a potential lack of coordination among sharing operators.

12.5.3 MOCN

The MOCN functionality allows several operators to jointly operate some elements of the radio access network, but the principal difference is that they will be using shared carriers, as opposed to using individual separate carriers in MORAN/MOBSS. Figure 12.48 depicts a Multi-Operator Core Network sharing scheme. This has immediate implications both for the mobile stations and for the shared components of the network. The used carrier frequency may be a regular frequency used by one of the operators, but also may be a separate one, dedicated strictly to the shared part of the network. Note that the participating operators may decide upfront to refarm their GSM/WCDMA/LTE networks in such a way to facilitate the MOCN-based network sharing.

There is also a challenge to identify the network in the system broadcast, as mobile stations of each participating operator will properly obtain the shared network identity. Obviously enough, the shared nodes need to have mechanisms for policing the traffic of each operator according to agreed levels of service, and also have to be able to correctly route the user and control plane data so that they reach the appropriate destination Core Network. The

MOCN feature was added to the WCDMA in Release 6 and was built in to the LTE standard since the beginning (Release 8). The GERAN standards offer partial support of the MOCN starting from Release 10, with the full support available from Release 11. Note that the Core Network components are not shared, although the name of the functionality might suggest that.

MOCN functionality has been made possible thanks to the inclusion of multiple PLMN IDs in the cell broadcast message. In LTE, this takes the form of the "PLMN identity list" present in the SIB 1 and containing up to 6 entries. Each LTE UE can read entire information contained there, so immediately becomes aware of the existence of MOCN. By default, the first listed PLMN is the primary PLMN in that cell. The situation is slightly different in WCDMA, where the support of multiple network identities as a later add-on. The usual PLMN identity present in the MIB has become a "Primary PLMN identity," and a new optional information element has been added to the MIB, carrying "Multiple PLMN ID list," which contain up to five additional PLMN-IDs. Additional related modifications have been added to SIB 3, 11 and 18 (PLMN-specific access restrictions, multiple PLMN identities of neighbor cells). All WCDMA UEs compatible with Release 6 and above autonomously detect and select the correct PLMN-ID, and consequently get connected to their home Core Networks, albeit using a licensed frequency of another operator. For pre-Release 6 WCDMA UEs, the multiple PLMN ID list is not visible, so these UEs can only read the primary PLMN ID. This PLMN ID could be added to the list of equivalent PLMNs.

A list of equivalent PLMNs is sent to the mobile after the GPRS attach, EPS attach, Location Area/Routing Area/Tracking Area Update procedures. The actual list sent to the mobile may depend, for example, on the IMSI of the subscriber (its HPLMN) or the area where the mobile is going to register. PLMNs in the list together with the PLMN of the network that sends this list are treated equally during the mobility procedures [11]. The same list is used in case of MM (Mobility Management), GMM (GPRS Mobility Management) and EMM (EPS Mobility Management) [12]. Provisioning of roaming services in the certain areas is facilitated by forbidden Location Area/Tracking Area concept – for details, refer to [11].[9]

If the shared network identity is not forbidden[10] for these UEs, they will be able to connect to the shared eNodeB. It is therefore advisable to use as the primary PLMN an identity different from the PLMNs used before the sharing agreement since the mobile station would remove from the list of Equivalent PLMNs those identities that are on the list of forbidden PLMNs. A new functionality is needed to allow these users, who are unaware of the existence of multiple Core Networks, to reach the one that is appropriate for them. This is called a Core Network Node redirection. At UE attach, the RNC assigns a random CN (other decision logics can also be applied, e.g., weighted round robin) to which the initial NAS message will be sent. If the selected CN is not appropriate for that UE, the relevant MSC sends back to the RNC a Redirection Request message. The RNC probes another CN, and does it until a CN that can serve the attaching UE is found. Similar equivalent procedures are relevant for the registration to the PS domain. The resolved association UE-CN is remembered by the RNC. Therefore, the pre-Release 6 WCDMA UEs can also access their home Core Network in the MOCN environment, but the attach procedure may take somewhat longer [10]. Moreover, a certain control over PS and CS registration is needed for pre-Relase 6 WCDMA UEs. Coordination of these registrations aims at assuring that the same Core Network operator serves the user from the PS and CS perspective. This could be achieved either with the help of an optional Gs interface that connects MSC and SGSN or via dedicated functionalities in RNC if the Gs interface is not implemented [10].

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[9] Apart from the procedures described above, new option of Equivalent HPLMN (EHPLMN) list that replaces the HPLMN derived from IMSI was introduced in 3GPP Release 6 [23.122]. The network the PLMN of which is the highest one in the EHPLMN list is selected by the mobile during PLMN selection process. The EHPLMN list is stored in the (U)SIM card.

[10] If Location Area/Routing Area/Tracking Area Update is rejected by the network with the cause "PLMN not allowed," such a PLMN is included in the forbidden PLMN list permanently stored in the SIM card. This entry could be deleted only if LAU/RAU/TAU triggered manually by the user is accepted.

The MOCN feature for GERAN network, fully available in 3GPP Release 11, is realized along the principles used for WCDMA case. In Release 10, where a partial support of MOCN has been introduced, the air interface is left unmodified, and therefore no multiple PLMN list will be introduced, thus a single PLMN ID will continue to be broadcast. It is naturally recommended that this single shared PLMN identity is a new one, seen by the mobile stations of each operator as an equivalent PLMN. The association of the appropriate Core Network will be performed by the BSC using the rerouting mechanism similar to that of the WCDMA. It is repeated that this procedure is practically invisible to the user, as the access request is not rejected while the BSC probes the available Core Networks. In order for this procedure to work, support for the A-flex and Gb-flex is necessary. As the radio interface remains untouched, all GSM mobile stations are compatible with MOCN solution as standardized in Release 10. Release 11 extends the GERAN standard to support full MOCN [13]. The multiple PLMNs (up to four additional ones) are introduced, using the Extended BCCH feature. For backward compatibility with pre-Release 11 UEs, a Common PLMN equivalent to each operator-dedicated PLMN should still be broadcast. However, for the UEs supporting MOCN, there is a possibility to forbid selection of a Common PLMN and consider only individual PLMNs to access the shared network and avoid possible redirection between Core Networks. Additionally, each PLMN may optionally be associated with the list of appropriate Access Classes to be used by mobile terminals while trying to access particular PLMNs [14].

In order to hide from the end user the fact that their mobile terminal is currently served by the shared component of the network, the Network Identification and Time Zone (NITZ) feature may be used [15]. This functionality is often used to set the clock to the local time zone for travelers, and also to update the clock to the daylight saving time changes. It also allows the serving network to send the network name within the mobility management procedures. The mobile terminal may use this name instead of the one stored in its memory. However, the network names stored on the SIM card take precedence over those sent via NITZ or stored in the mobile station memory. In a shared network NITZ can be used to send different network name for subscribers of participating operators. It is possible to associate at least 10 PLMN identifications with the same operator name. While NITZ is not a mandatory component of network sharing scenario, it is quite a useful functionality from the point of view of the end user.

Due to the fact that all operators share a single physical piece of hardware, only one of the operators (or a selected third party operator) can actually install and manage the shared radio access nodes, that is, do the network planning, install and maintain the node, collect alarms, keep track of performance counters, and so on. Other operators have to negotiate specific agreements but in fact the shared elements will not be fully integrated into their network. The specific areas where the operators have to reach satisfactory degree of consensus are related to network rollout (planning, dimensioning, topology, provisioning of transport/backhaul) and operation (OAM, upgrades). It is also necessary for the participants to agree on the specific details of the financial contribution scheme of CAPEX and OPEX (e.g., equal share, or in function of traffic volume). The specific details of the operation of the shared network are dependent on solutions available in each case, for example the mechanisms for load steering between the operators sharing the RAN will depend on whatever exists in the installed equipment (e.g., equal vs. prioritized capacity sharing) and dedicated features designed for MOCN. This may take the form of solutions that will allow dedicating a certain capacity for each operator, for example, in the form of a guaranteed bit rate per operator plus some floating capacity allocated on a per-need basis. This policing functionality may also be linked to admission control mechanisms, aiming at proactively avoiding the congestion.

Note that also the backhaul link can be either common or separate, the former calling for appropriate packet network load balancing functionality.

One of principal benefits of MOCN is that the participating operators can jointly use part of their bandwidth to create a much wider overall bandwidth, making it possible to offer much higher data rates for individual users. Additionally, trunking gain comes into play, as the usage of a single larger band is more effective throughput-wise than having two halves of that band used separately. Moreover, signaling overhead is more favorable for wider bandwidth allocations. If a 1.4 MHz band is used for LTE deployment, only slightly more than half of the band is available for traffic channels scheduling (51%), while in 5 MHz deployment, 63% of the resources can be allocated for the actual traffic. This difference originates mostly from the different guard band overhead (cf. Table 12.2) and the specific layout of PBCH and the synchronization signals.

12.5.4 National Roaming, Geographical Roaming and IMSI-based Handover

The national roaming feature offers another possibility for an operator to provide coverage to their subscribers[11] without having physical equipment deployed at a certain area, as depicted in Figure 12.49.

The underlying idea is the same as in case of roaming in international network, and requires the participating operators to sign a roaming agreement. As a result, the PLMN ID of the hosting party is added to the allowed PLMN list of the subscribers of the operator in question. Such an agreement can be reciprocal, or not, depending on the decision of the participants. In national roaming, the roaming agreement covers the area of the entire country. In the case of geographical roaming, the roaming area covers only selected parts of the country, these could be, for example, rural areas, isolated islands, and so on, but the participating operators will also own and operate their own independent networks. The UEs operating in such an environment need to apply different mobility procedures when inside the visited area and when at the border between home and visited network. Usually the area where the user is allowed to roam is delimited by forbidden zones (e.g., routing or tracking areas), causing the roaming user to reselect to another PLMN (the home PLMN in this case).

In idle mode, access control of the particular group of users to the certain cells may be performed with the help of Core Network procedures related to handling of Equivalent PLMN functionality. In order to fully benefit from the PLMN-aware traffic steering, the dedicated mode has to be integrated in this process as well. In this case, a certain amount of support from

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[11] National roaming does not require any particular support from mobile stations, but there may be some limitations with respect to support for national roaming in case of very old GSM phase 1 mobiles.

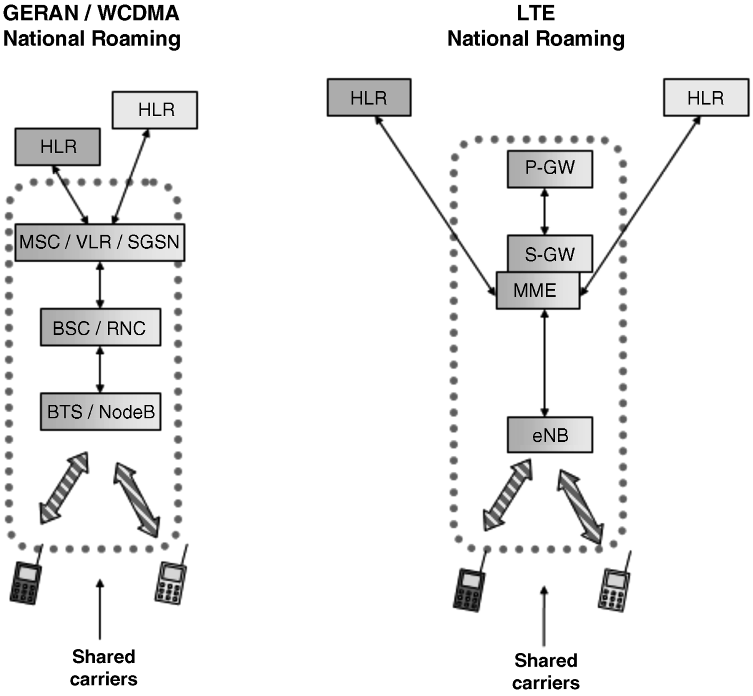

Figure 12.49 National roaming scenario.

the Radio Access Network is needed. In order to retrieve the home PLMN of the end user, the IMSI identity – where the MCC (Mobile Country Code) and the MNC (Mobile Network Code) are embedded – could be used. Having the user's IMSI available, BSC[12] or RNC could route the traffic that is, perform the handover only towards the predefined cells (either 2G or 3G) that were designated as valid cells for the group of users to which the given subscriber belongs. In order to optimize this procedure, certain restrictions with respect to the measurements of the neighboring cell may additionally be applied. In LTE, the support for such a scenario is embedded in the "Index to RAT/Frequency Selection Priority" (RFSP Index) concept where the UE-specific RFSP index could be retrieved from HSS and sent to the eNodeB via MME and it could be subsequently used to apply UE-specific RRM strategies including the evaluation of potential handover target cells. Note also that applicability of IMSI-based traffic routing may be extended beyond the MCC and MNC part of the IMSI that is, also to MSIN (Mobile Station Identification Number) – only if reasonable users' differentiation may be performed thanks to such an extension.

Typically, IMSI-based handover functionality may be implemented in the shared network environment where, for example, two operators share the GSM network while keeping their WCDMA networks separate. In order to avoid making national or geographical roaming

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[12] Due to the sensitivity of IMSI, it is generally not recommended sending this identity via air interface. Instead, BSC may receive an IMSI information from the MSC in, for example, Common ID or Handover Request message. Note, however, that providing such information by MSC is not mandatory unless the Dual Transfer Mode (DTM) is implemented in the given network [3GPP 48.008].

Table 12.9 Regional roaming scenario.

LAC	Resources of operator A Subscriber		Resources of operator B Subscriber	
	Op. A	Op. B	Op. A	Op. B
2G Urban LACs	Allowed	Restricted	Restricted	Allowed
3G Urban LACs (2100)	Allowed	Restricted	Restricted	Allowed
2G Rural LACs	Shared spectrum			
3G Rural LACs (900)	Shared spectrum			

agreements on the 3G side, the operators may introduce PLMN-aware traffic steering procedure in the GSM. Thanks to this policy, subscribers of operator A will measure only WCDMA cells of operator A and they could be handed over only to these cells. Similar rules will apply for subscribers of operator B. This functionality will be especially important in the areas where WCDMA coverage ends, leading usually to frequent inter-RAT procedures performed at the edge of the 3G network. In the intra-GSM scenario, the IMSI-based handover could be applicable, for example, in the geographical roaming case where only a certain part of the network is shared by the operators (e.g., in the rural areas) and there is a strong need to route the traffic reasonably in the areas where shared and non-shared parts of the networks join. An example of geographical-based roaming agreement between two different operators partially sharing GSM and WCDMA networks is presented in Table 12.9.

12.6 Hardware Migration Path

Migration towards Long Term Evolution (LTE) requires from the operators extra expenditure on hardware modernization. In order to support the LTE technology, new base station hardware needs to be implemented since the legacy 2G/3G technology-oriented equipment already installed on sites is not LTE-capable. New hardware will complement the existing network infrastructure, which in the majority of cases is going to be still maintained to support 2G/3G systems in parallel with LTE deployment. Thus, the LTE introduction will imply additional investments and an increase of operational expenditures (OPEX) because more hardware has been used in the network. At the same time the operators are forced to reduce costs and improve the operational efficiency of the network. Among others, this is due to continuous increase in energy costs, which are already the major component of the operator's OPEX and will increase in future.

Different LTE deployment scenarios are currently analyzed (e.g., hot spot areas only, continuous coverage in city areas, etc.), however, in most scenarios re-use of existing 2G/3G sites is considered. This is the solution that allows the operators to save money, which is usually spent on the construction of new sites; on activities such as site acquisition, site design, civil works, and so on. In the case of 2G/3G sites re-use, the base station hardware dedicated to LTE as well as the antenna system will be co-located with other technology equipment. In other cases (e.g., a greenfield operator), LTE sites will be built from scratch unless other operators' infrastructure is shared. Hereafter, the re-use of existing sites is considered only, as it is likely for the majority of operators and it is directly related to the hardware migration path.

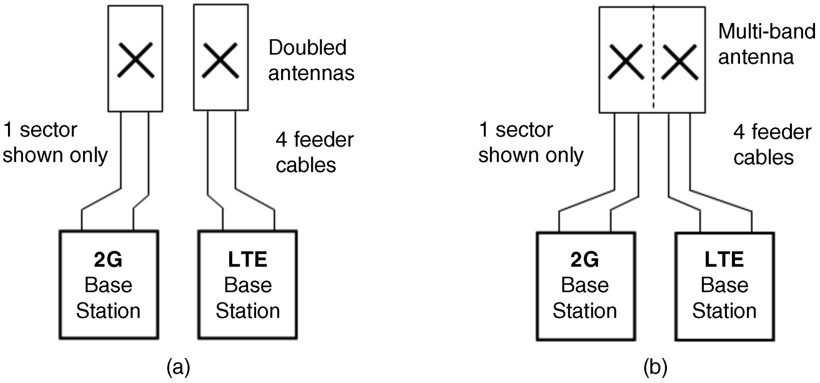

Figure 12.50 Co-located antenna systems (base stations work in different frequency bands); (a) separate single-band antennas, (b) multi-band antenna.

12.6.1 Co-Located Antenna Systems

There are several alternative methods available to co-locate different technology antenna systems. Thus, the operators have again some room to optimize LTE deployment costs. First of all, the selection of a preferred method depends on whether the co-located systems will operate in the same or in different frequency bands.

12.6.1.1 Co-Located Systems – Different Frequency Band

The co-located antenna systems can be composed of either separate single-band antennas or can be built using multi-band (dual-band or triple-band) antenna types (Figure 12.50). Hence, an LTE-related single-band antenna must be installed in addition to the existing one or it needs to be replaced bya multi-band antenna type. In both cases, some site reconstructions must be done to allow the system extension.

With multi-band antennas the necessary number of antennas per site is minimized, however, the reduction of the visual impact is still a big challenge in the majority of the extension scenarios.

When multi-band antennas are used, the same azimuth applies for all related Radio Access Technologies (RAT). Since the network plan for the existing system should not be changed, the planning process for the LTE system has to take care of such limitations.

Each of the frequency bands used on site requires dedicated feeder cables to be installed on site, which is another aspect to be considered when modernizing the existing antenna system. By using diplexers or triplexers, the requested number of feeder cables per sites can be reduced, as shown in Figure 12.51.

Diplexers (triplexers) are filter units that combine and separate the outputs of two (three) transmitters of different frequency bands into a common feeder cable. They also perform the reverse function of accepting a received signal of different frequencies and splitting them into their respective receivers. In some multi-band antenna types, a diplexer (triplexer) is already embedded in the antenna panel. Use of such antenna types makes it unnecessary to mount the external diplexer (triplexer) close to the antenna. It should be remembered that additional losses in the downlink and uplink direction are introduced when those new elements are applied in the

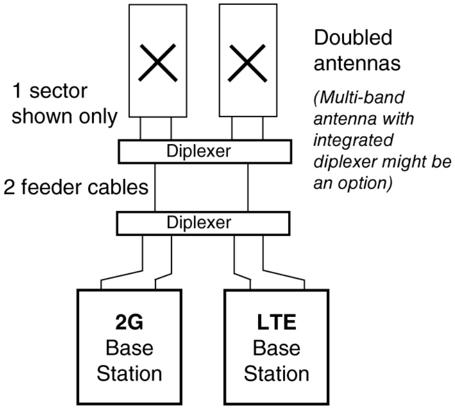

Figure 12.51 Co-located antenna systems with common feeder cables (base stations work in different frequency bands).

antenna system. Thus, the impact of such a solution on LTE planning as well as on co-located technology performance needs to be considered. With separate single-band antennas as well as with multi-band antenna types, it is possible to support multiple streams transmission in the downlink direction for the LTE system (e.g., 2 × 2 MIMO). This is because the LTE signal can be transmitted via both antenna lines available in a typical antenna system.

12.6.1.2 Co-Located Systems – the Same Frequency Band

The existing antenna system can remain untouched if LTE is deployed in a frequency band that is used by radio access technology that is already operating on site, for example, the so-called frequency refarming solution. In that case, co-located RATs may use a common antenna system. Since no changes are introduced into the antenna system, the operator can roll out LTE much faster than with dedicated or multi-band antennas. Moreover, the operator can save money that would be spent on the modernization if the existing antenna system had to be changed. With a common antenna system both co-located technologies must use the same antenna azimuths and antenna tilts.

Typically, a two-branch reception diversity is applied in a base station to improve the receiving system sensitivity. For that purpose, in each of the configured on-site sectors two antenna panels (or single cross-polarized antenna) need to be connected via two antenna lines to the base station equipment. Downlink transmission can be realized via a single antenna panel or via both antenna panels. In the case of the 2G system, there are usually several transmitters (TRXs) being used in each sector. Since the signals coming from all TRXs need to be combined to the antenna line, additional attenuation is introduced into the transmit path by the combining equipment. The attenuation increases with the number of combined TRX outputs, hence the option to minimize the combining losses is to split the transmit paths into two separate branches connected to two antenna panels.

If co-located RATs are going to use a common antenna system, the available transmit (TX) and receive (RX) paths need to be shared between the systems. RX signals from both antenna panels need to be distributed between the two pairs of receiver branches: to primary receivers (RX) and to diversity receivers (RX-D) of the co-located base stations. Since two antenna lines

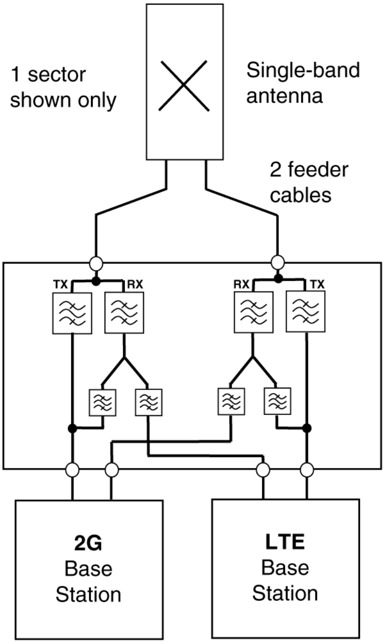

Figure 12.52 Co-located antenna systems with external RX/TX path combiner (base stations work in the same frequency band).

are available, it is possible to connect the co-located systems to the separate transmit branches. Hence, downlink losses are not increased for the LTE system. However, for 2G, all the TRXs have to be combined to the single TX path only, which can imply for some cases increased combining losses comparing to the double TX antenna solution. An important aspect is that due to the single transmit path assigned to each of the systems, LTE cannot support multiple streams transmission. Anyway, the external TX/RX duplexer must be installed to separate TX and RX paths before they are connected to the base station equipment. Figure 12.52 shows an example of the external hardware solution that allows both the co-located systems to use common feeders and antennas.

In some cases, it might be possible to use the common antenna system without extra hardware being installed. Modern base station types offer in their front-end modules an RX output signal, which can be used for external purposes, for instance, it can be delivered to another base station as an RX diversity signal. Using such RX output signals, the diversity paths can be exchanged between both co-located bases stations. The RX path to primary RX receivers as well as transmit path remain exclusively within its “mother” base station hardware (Figure 12.53).

It should be remembered that the RX performance of both base stations may change in comparison to the standalone scenario. This is due to the fact that the RX diversity path will suffer a certain amount of certain degradation as it goes through additional active and passive HW components of co-located base station. TX paths are not affected since each base station transmits via its own TX path, however, for the 2G base station there is again the need to combine all TRXs to single transmit path.

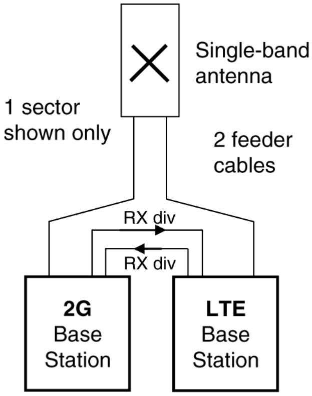

Figure 12.53 Co-located antenna systems with RX paths shared (base stations work in the same frequency band).

12.6.2 Co-Location with Shared Multi-Radio Base Station

The constant development of the mobile communication systems has accelerated upgrades in the area of base station technology. LTE could be deployed using software definable radio, where instead of dedicated hardware there are software components applied to support base station-related functions (e.g., channel coding, modulation, filtering, etc.). In parallel, wideband transmission and reception technology has been introduced, using multi-carrier power amplifiers and wideband receivers. In a traditional base station, a single-carrier technology is used with a dedicated transceiver and power amplifier units. In a multi-carrier unit, the number of carriers can be freely configured (including various multiple transmission schemes), enabling flexible capacity expansion and reduced power consumption. Multiple signals are transmitted through a broadband power amplifier, which has its power shared among defined carriers. Multi-carrier technology was first applied in 3G base stations, but nowadays it is re-used for LTE as well as for the 2G system. Since base station functions are realized by dedicated software components, it was possible to develop a common hardware platform for 2G, 3G and LTE technology. It means that all the technologies can be handled using the same set of hardware elements. Moreover, different RATs can operate in parallel with carrier signals being transmitted and received via the same radio frequency unit. As a result, no additional hardware needs to be installed to allow a common antenna system to be used by different technologies operating on site. However, since the radio frequency unit is designed to support a single frequency band, LTE must be deployed in the already used on site frequency band to take advantage of the minimum hardware configuration (Figure 12.54).

LTE deployment gives the operators a unique opportunity for low cost 2G hardware modernization, especially in the case of LTE being deployed in 2G frequencies. Owing to multi-radio hardware, both technologies can work on the same hardware platform, which brings OPEX savings on spare parts, energy consumption, maintenance activities, and so on. Since the existing antenna system can remain untouched, LTE deployment can be done with minimum investment and within a short time frame. That is why it should be considered by the operators the optimum solution, especially when frequency refarming is one of the options.

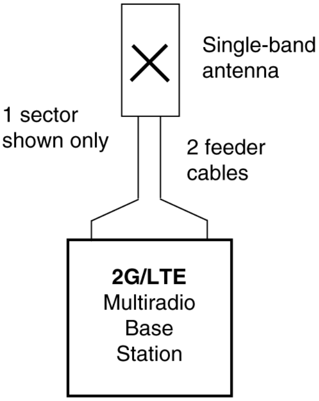

Figure 12.54 Co-location with shared multi-radio base station (base stations work in the same frequency band).

12.7 Mobile Backhaul – Towards "All-IP" Transport

12.7.1 Motivation to IP Evolution in Mobile Backhaul

The continuous evolution of 3GPP standards going beyond GSM/EDGE and UMTS Release 5, and in particular the introduction of High Speed Packet Access (HSPA) and soon later Evolved HSPA (I-HSPA), has led to an enormous growth in mobile traffic worldwide. However, this unprecedented traffic boom is not driven solely by the emergence of new radio access technologies but also by fierce competition in the mobile market, resulting in flat rates as well as the commercial availability of a new generation of handsets with abilities to run advanced applications and services being often Internet-based. The coincidence of these above-mentioned elements (higher peak throughputs, new pricing policy for data, and online applications) also has brought about a change of characteristics of mobile traffic from voice dominant to data dominant.

Nowadays it is clear that the traditional hierarchical (DS0, E1, STM1, . . .) transport networks, which obviously were designed for mobile voice and low speed data, are not efficient enough for bursty traffic as they use a rigid allocation of basic transport units (e.g., DS0 in the case of legacy PDH/SDH-based transport) resulting in bandwidth separation for different planes and limited overbooking capabilities. Moreover, the E1/T1 transmission networks do not offer flexible scalability as capacity extensions are made in large steps (e.g., at least 2 Mbit/s in the case of E1 lines) which means that provisioning of extra bandwidth for numerous Base Stations will account for a considerable contribution to the total network costs (although just a fraction of the installed extra capacity may actually be needed). To summarize, the principles which are fully justified for voice-dominant traffic become too wasteful when it comes to the transmission of huge bursts of data. Therefore, improvements in transport efficiency leading to lower transport costs are the first and main driver of the mobile backhaul modernization necessary to cope with the steadily growing bandwidth demand.

The improvements in transport efficiency are absolutely crucial for network operators to reduce the network costs but quite recently, especially with the introduction of sophisticated Internet-based and always-on applications, another driver of backhaul modernization has become more and more important, namely, the user perceivable network performance. On the

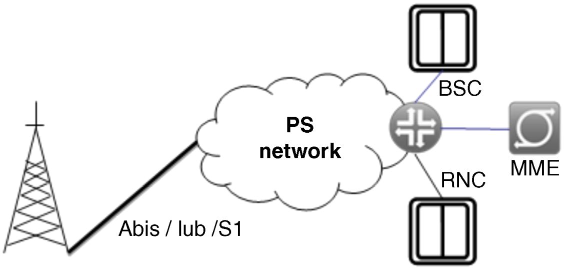

Figure 12.55 "All-IP" transport.

one hand, aggressive advertisements set high customers' expectations in terms of peak (i.e., not average) throughput rates. On the other hand, providing the advertised speeds to several customers simultaneously would lead to the immediate need for an E1/T1 capacity extension in most of the Base Stations as long as the legacy transport is in use (even though such extra capacity might not necessarily produce proportional revenues as those are correlated more with transmitted traffic volumes than with peak throughputs). This means that, to be successful, the network operators are supposed to achieve at the same time two (often contradictory) targets related to transport efficiency and customer satisfaction.

Taking these challenges into account, the migration to a new transport technology that overcomes the existing limitations of the legacy PDH/SDH architecture in terms of the network capacity, transport costs, and at the same time enables a great experience for mobile users is inevitable. Meeting these extensive requirements is feasible through the deployment of flat, all-IP transport networks (see Figure 12.55).

As a result of replacing the legacy transport infrastructure with an IP-based one, a bunch of benefits can be observed, which will allow mobile operators both to manage the "traffic explosion" and to remain profitable:

- significant bandwidth savings thanks to the optimization of the payload structure and the introduction of greater flexibility in bandwidth usage (pooling of resources, traffic aggregation and overbooking);
- far better scalability due to the introduction of wideband Ethernet connectivity at the Base Station as well as at the Core side, which evaluates transport capacity adequately to the actual traffic load and peak-to-average profile;
- Ethernet transport offers much lower "cost per bit" which contributes to a further reduction in operational expenditures;
- re-use of common transmission concepts regardless of the radio access technology: IP transport can now be applied to GSM/EDGE as well as UMTS/HSPA networks; furthermore, sharing of common transport in a multi-RAT environment leads to synergies which maximize the overall efficiency (statistical multiplexing, common maintenance);
- simplified transition to a flat architecture which aims at the reduction of network elements by the integration of some functionalities originally executed in dedicated entities, what helps to reduce end-to-end delay which is, in turn, a prerequisite for the provision of real-time services. For instance, 2G transcoding functionality partly disappears and the rest can be moved to the Media Gateway; another example can be part of controller intelligence which is either implemented in the Base Station or even entirely integrated as in LTE eNodeB.

The additional advantage lies in the fact that the abovementioned features do not have a negative impact on the user experience. Quite the contrary, it is possible to ensure similar performance such as that achievable in TDM networks by means of proper planning and configuration.

Ultimately, migration to a flat all-IP transport network paves the way for the global and smooth launch of the Evolved Packet Core (EPC). This is not only because E-UTRAN does not support legacy TDM transport at all, but also because the sooner IP transformation is initiated, the more mature packet backhaul will be available during the LTE introduction, which simplifies its roll out to a great extent. For instance, from the radio access perspective, it would then be similar to the integration of another technology to the existing 2G/3G installations rather than beginning something revolutionary.

12.7.2 Transport Aspects in Packet Backhaul

Migration to full packet transport involves the replacement of the TDM E1/T1 links with Ethernet-based Packet Switched Network (PSN). The PSN introduces some complexity that is not present in TDM-based transport. Hence, specific solutions are leveraged to improve the reliability and control the performance of Ethernet networks. In that sense, the IP evolution requires and provides the means to effectively deal with transport impairments, synchronization assurance, higher security threats and lack of guaranteed bandwidth [6].

The capability of a PSN to serve as a transport medium is expressed in the level of transport impairments understood as packet loss rate, packet delay and delay variation. The presence of such impairments in every PSN, although unwanted, is unavoidable. However, if the packet loss rate, packet delay and delay variations are kept within a certain range, then their impact on performance is negligible. Therefore, the predefined values of transport impairments must be rigorously maintained within the required service level to preserve the performance such as that in TDM transport.

Delivery of a synchronization reference signal to every Base Station with the required frequency and time accuracy is absolutely necessary to ensure the proper operation of both radio interface and the transport network. In legacy transport, as long as TDM connectivity is present at each Base Station, the synchronization signal is efficiently distributed over the network by means of the E1/T1 lines connected to the controller and furthermore to the core. In packet backhaul, the synchronization chain no longer exists as Ethernet is by its nature asynchronous. Thus various synchronization techniques are made available to address this issue; and for now Timing over Packet which is based on Precision Time Protocol defined in [16] is the most preferred one. In this solution there is a master device which generates timing packets and transmits them to a dedicated Base Station (where a slave device is installed) using a unicast connection. Timing packets traversing the PSN obviously experience delay and delay variation but the slave function implemented in the distant node performs the recovery of the original clock by means of sophisticated algorithms implemented in it. Each Base Station must have its own connection with the source of time-stamped packets. One of the possible alternatives to clock recovery algorithms is to adapt the basic synchronization concept known from the traditional TDM-based transport, that is the transmission of the reference signal over the physical layer. In the case of IP transport, this is possible by using the Synchronous Ethernet [17]. In this method, a timing signal is relayed from the primary master to the target Base Station using synchronization ports of interconnected Ethernet switches. The solution provides an accurate clock signal independently of the PSN load when it is supported at every node between the reference source and the final destination. Other methods relying on external synchronization sources (e.g., a GPS receiver or dedicated E1/T1 line) are typically seen as too expensive and thus their applicability is rather limited.

Replacement of traditional TDM-based transport with packet backhaul raises higher security concerns especially when transport is realized through large and public PS networks. In such a scenario, mobile traffic is typically shared with various systems and managed by different operators with different security standards. Global accessibility to packet networks in the context of security is not helpful, either. Hence the ordinary security threats related to eavesdropping or unauthorized data modification are now present not only in the radio interface but also "propagate" over the access part of the networks and relevant countermeasures must be adapted to the IP over the Ethernet transport specifics. Thus., a set of features that aim at mitigating the risk of attacks and protecting every type of traffic is available. Firewalls and security gateways are installed in front of important network entities or interconnecting nodes, IPSec provides security measures for user authentication as well as data encryption and integrity, certification management ensures security associations between network entities and nodes.

Enabling multi-radio access technologies (with very different bandwidth needs) and shared packet transport (where available transport capacity is affected by load fluctuations) introduce some uncertainty on how to guarantee enough bandwidth to handle the traffic served by the radio interface. This can be ensured by proper Quality of Service (QoS) definition throughout the transport network. Such a definition should reflect the fact that particular services have different delay tolerance, on the one hand, and produce different incomes, on the other. Therefore, packets can be treated with managed unfairness, for instance (depending on operator strategy), voice and real-time data take precedence over non-real-time and best effort data services. In addition to advanced QoS engineering, some congestion control mechanisms are implemented to automatically adjust the data volume to be sent on the backhaul depending on the PSN overload conditions.

The abovementioned functionalities are fully integrated with regular network devices (both at the Base Station side as well as in the Core Network) so that transport migration is coordinated with the availability of SW and HW features supporting the ongoing network modernization and transport evolution.

12.8 LTE Interworking with Legacy Networks for the Optimal Voice and Data Services

The optimal interoperability of LTE with the legacy networks requires efficient inter-system management mechanisms dedicated to both connected and idle modes. Generally, LTE and the legacy networks interworking can be considered in two different, although often interwoven, contexts, namely, data services and voice services. While interworking in the context of data services can be expected to be the seamless cooperation of PS domains of the considered systems, interworking in the voice services context is a more complex issue. This is because of specific methods of voice services realization in LTE being a consequence of the lack of the CS domain in the EPS architecture.

The aim of this chapter is to introduce selected LTE and legacy networks interworking techniques that are intended to provide the optimal performance of both voice and data services. The main focus is on practical deployment aspects. The discussion provided in the following sections is based on the latest versions of the 3GPP specifications available at the time of writing this book. Section 12.8.1 is dedicated to tri-directional inter-system mobility management for optimal data performance. Sections 12.8.2 and 12.8.3 provide discussion on how to efficiently ensure the continuity of voice services across different technologies. In Section 12.8.4, a concise discussion on the Idle Mode Signaling Reduction (ISR) functionality is included.

12.8.1 Inter-System Mobility Management for Data Services

The following functionalities have been defined to enable PS-related interworking procedures from GERAN to E-UTRAN:

- cell reselection;
- Network Assisted Cell Change (NACC);
- Network Controlled Cell Reselection (NCCR);
- PS handover.

The counterpart features that were standardized for E-UTRAN to perform Radio Access Technology (RAT) change to GERAN are listed below:

- cell reselection;
- RRC connection release with redirection;
- Cell Change Order (optionally with NACC);
- PS handover.

Regarding WCDMA – E-UTRAN interworking following procedures were standardized:

- PS handover;
- cell reselection;
- RRC connection release with redirection.

All these procedures are described in detail in the next sections.

12.8.1.1 UE-Controlled Cell Reselection

The primary means of changing the serving cell in the GPRS/EDGE network is still based on the reselection procedure – even for mobiles in Packet Transfer mode where the Temporary Block Flow (TBF) is established and there is ongoing data transmission. This means that during every cell change that occurs during data connection, the mobile has to temporarily leave the Packet Transfer mode and enter the Packet Idle mode. The interruption time during the PS transmission posed by the cell change procedure may be of the order of even few seconds in the extreme case if, for example, the source and target cell belong to different Routing Areas. This is one of the key differences between handling of the users' mobility inside GSM and inside the LTE network that has to be considered when analyzing inter-RAT mobility management.

In principle, a UE-controlled reselection algorithm is the same for GSM Idle, GPRS Packet Idle and GPRS Packet Transfer mode.[13] In the pre-Release 8 algorithm for 2G to 3G,

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[13] Support for PBCCH – with the help of which GSM PS/CS differentiation for mobility procedures could be performed – was removed from 3GPP Rel. 9 onwards.

UE-controlled inter-system cell reselection (what is called the cell-ranking algorithm) apart from the minimum CPICH Ec/No and RSCP criteria the target WCDMA cell has to satisfy,[14] the signal strength difference between the GSM serving cell and the target UTRAN cell was checked against a predefined threshold. It was concluded, however, from the GSM-WCDMA interworking experience that use of such a direct comparison between the signal strength of both systems may lead to undesired mobile behavior, such as the constant changing of the RAT that the mobile is camped on. Moreover, the possibility of arbitrary high settings of the signal strength offset parameter (FDD_Qoffset) to effectively prioritize WCDMA over GSM network was often used by the operators, leading actually to coverage-based inter-RAT reselection [18].

Regarding WCDMA network, the inter-RAT reselection algorithms are applied for the mobiles that are in Idle, URA_PCH, CELL_PCH and CELL_FACH states. The mobility of UEs that are in the CELL_DCH state is governed by the handover procedures.

The new concept of so-called absolute priorities was introduced in 3GPP Release 8 to support inter-RAT reselection between GERAN, UTRAN and E-UTRAN, including also the intra-E-UTRAN/UTRAN inter-frequency cell reselection. In this algorithm, a direct comparison between signal levels of different RATs is no longer required. The new idea is based on unambiguous cell reselection priority order between different RATs without predefined offsets. In 3GPP Release 8, for the target GERAN or E-UTRAN cell with a higher priority than the serving one, only the minimum signal strength criteria have to be satisfied for this cell in order to trigger the inter-RAT reselection to it. In the case of target 3G cell, the minimum quality criteria (CPICH Ec/No) are also checked. In 3GPP Release 9, the minimum quality criteria (based on RSRQ) were also introduced for target LTE cells. The mobile can reselect a lower priority cell only if no suitable higher priority cells could be found and moreover no optimal cell could be found in the serving layer/RAT. In the case of LTE, in 3GPP Release 8, reselection to lower priority cells is triggered by the low RSRP level of the serving cell. In 3GPP Release 9, as an option, it could be triggered by the low RSRQ level, hence reselection can be performed at any place, where high interference appeared, within the cell and not only on the cell edge.

More flexibility was added to the time aspect of the inter-RAT procedures that is, the timer during which all the inter-RAT reselection criteria had to be met was changed from s fixed 5 seconds (as in the case of GSM-WCDMA cell reselection based on cell ranking) to parameterized timer.

The typical example of inter-RAT reselection (details in [19]) from low priority GSM cell to high priority LTE cell is presented in Figure 12.56.[15] The counterpart priority-based inter-RAT reselection in the opposite direction (details in [20]) is presented in Figure 12.57.[16]

The information about priority of different layers is available in:

- System Information type 2 quarter in GSM [14];
- SIB19 in WCDMA [21];
- SIB3, SIB5, SIB6, SIB7 and SIB8 in LTE [22].

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[14] The latter criterion is optional for pre-Rel. 5 mobiles.

[15] It was assumed that THRESH_E-UTRAN_high_Q was not provided to the mobile meaning that LTE RSRP is evaluated instead of LTE RSRQ while being in GSM.

[16] It was assumed that threshServingLowQ is not included in SIB3 meaning that reselection to lower priority layers is triggered by the low LTE RSRP value instead of low LTE RSRQ.

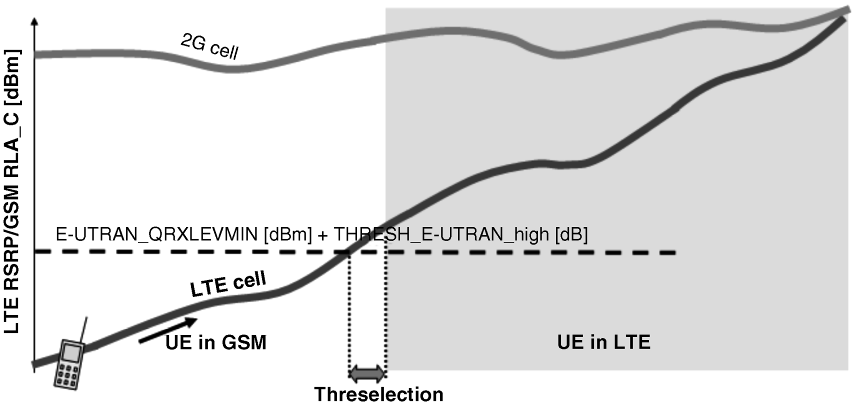
LTE RSRP/GSM RLA_C [dBm]
2G cell
E-UTRAN_QRXLEVMIN [dBm] + THRESH_E-UTRAN_high [dB]
LTE cell
UE in GSM
UE in LTE
Threselection

Figure 12.56 Inter-RAT cell reselection from low priority GSM cell to high priority LTE cell.

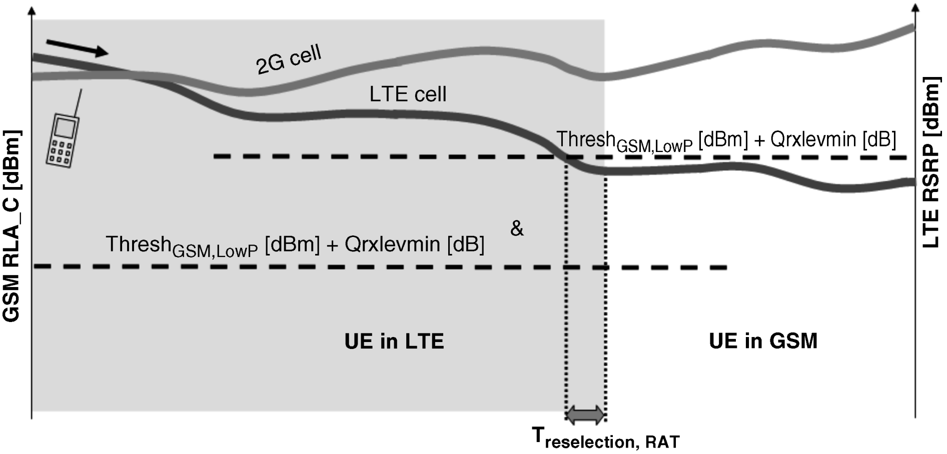
2G cell
LTE cell
Thresh$_{GSM,LowP}$ [dBm] + Qrxlevmin [dB]
&
Thresh$_{GSM,LowP}$ [dBm] + Qrxlevmin [dB]
GSM RLA_C [dBm]
LTE RSRP [dBm]
UE in LTE
UE in GSM
T$_{reselection, RAT}$

Figure 12.57 Inter-RAT cell reselection from high priority LTE cell to low priority GSM cell.

However, apart from common priorities to be used during the inter-RAT reselection process, it is also possible to set the mobile-specific individual priorities that could differ from the common list of priorities distributed in the BCCH. Such dedicated priorities may be sent in:

- Packet Measurement Order or Packet Cell Change Order [23] and Channel Release [14] messages in GSM;
- Utran Mobility Information [21] message in WCDMA;
- RRC Connection Release [22] message in LTE.

In such a way, certain per-user control over traffic routing may be assured.

However, the legacy algorithm based on the cell ranking has not been totally ruled out from inter-RAT procedures even for E-UTRAN-capable mobiles, leading to possibly complicated parameterization that has to be handled by the operator of the multi-RAT network. In the UE that is camped on the UTRAN network, the legacy cell ranking algorithm and priority-based algorithms may be used in parallel – the former in the direction towards GSM with the latter towards E-UTRAN. Moreover, it may occur that in UTRAN the legacy cell ranking algorithm is responsible for handling the reselection towards GERAN, while similar to GERAN to UTRAN reselection, a priority-based algorithm is used in the UE. In the case of cell reselection from GERAN to E-UTRAN, the situation is less problematic since it has been made mandatory by 3GPP to perform the inter-RAT reselection by the E-UTRAN-capable mobile camped on GSM solely in accordance with the priority-based algorithm, also towards UTRAN.

In order to achieve consistent behavior of the priority-based inter-RAT reselection procedures careful parameterization on each side of the involved systems has to be performed – the common policy with respect to RAT's priority has to be implemented first.

12.8.1.2 Network-Controlled Cell Reselection in GSM

The reselection process in the 2G network may be triggered exclusively by the mobile – as described in Section 12.8.1.1 or alternatively it could be network-controlled if the optional Network Controlled Cell Reselection feature is introduced in the network. The clear benefit of NCCR over UE-evaluated reselection is the network control over traffic distribution across different cells and layers and not the related cell reselection delay – that is in principle similar to the one for UE-controlled cell reselection.

The mobile station may be ordered to leave GSM and enter E-UTRAN also by means of a network-controlled cell reselection procedure during which in the Packet Cell Change Order message an LTE target cell could be included – similarly as it was earlier standardized for Inter-System NCCR towards WCDMA.

12.8.1.3 Network Assisted Cell Change in GSM

The functionality that was standardized by 3GPP to reduce the cell outage time caused by the generic reselection procedure in the GSM/GPRS network is called the Network Assisted Cell Change. The primary aim of this feature was to provide the set of crucial System Information messages transmitted normally in the BCCH of the considered, target cell already in the source cell. In the general case, an MS withholds the reselection process, enters what is called the Cell Change Notification (CCN) mode and waits for the neighboring cell data to be delivered to the mobile. With the help of this functionality the reselection time may be reduced even by 50% [6].

These procedures were originally standardized for the reselection that takes place inside the area under supervision of the given BSC (3GPP Release 4) but soon they were extended within 3GPP Release 5 to cover also non-trivial inter-BSC reselection.[17] The mechanism approved by the 3GPP to convey the necessary signaling needed for the distribution of System Information between BSCs is called RIM (RAN Information Management) [24].

Further extension of 3GPP specifications to cover the NACC procedure for the inter-system reselection cases from UTRAN to GERAN was included in 3GPP Release 6 [25]. Subsequently, this mechanism was inherited also by the LTE architecture. The support for inter-system NACC procedure is not symmetrical: while System Information messages are provided to the mobiles reselecting from UTRAN/E-UTRAN to GSM, these messages are not distributed for UTRAN or E-UTRAN cells to the mobiles that are about to perform inter-RAT cell reselection from the GSM network. In the latter case the mobile could enter CCN mode indicating the target 3G or LTE cell but it is not supported by any kind of System Information data of the target cell.

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[17] Original GSM architecture did not foresee the direct interface between two BSCs.

12.8.1.4 Mobility Management Events in E-UTRAN

Mobility procedures inside the LTE network and for the network changes from LTE to GERAN or UTRAN are handled by means of the evaluation of certain events that are related to both measurements actions (i.e., what kind of cells should be monitored) and the actual handover/cell change/redirection procedure. Thresholds for triggering given events could be absolute (typically for coverage handovers) or relative (typically for power budget handovers). Note that separate thresholds can be specified for different sets of ARFCN frequencies, which in combination with the timers mentioned below, provides a means of effective prioritization between various target cells. For all thresholds, additional hysteresis values to prevent from ping-pong effect may be applied. Apart from thresholds related to either signal strength or signal quality events' procedures are also governed by certain timers (what is called time to trigger parameters) that introduce appropriate time hysteresis in the mobility procedures. The shorter the timer is, the more responsive is the mobility algorithm. However, too short a timer leads to the ping-pong effect and unnecessary handover actions. All the events have to be considered jointly in order to assure proper mobility management. Details of event-based evaluation of network measurements are provided in [22].

12.8.1.5 PS Handover

Handover for PS services that initially was introduced for WCDMA starting from its first release was standardized for GSM late in 3GPP (in Release 6) and it is not widely deployed. Hence, although this procedure was adapted in 3GPP Release 8 also for the inter-RAT procedures between GSM and LTE in both directions, it is not expected to be broadly used in the early LTE deployments for handling GSM-LTE interworking. For further details related to this functionality in the GSM environment, refer to [10].

In contrast to GSM case, the PS handover in WCDMA is the principal functionality that assures seamless mobility for data transactions. This functionality was inherited by the LTE architecture and it is the only available option to change the network directly from UTRAN CELL_DCH state to LTE RRC_CONNECTED state and vice versa.

Typically, the measurement process of target cells is started in the LTE network once the RSRP or RSRQ of the serving LTE cell falls below a predefined threshold leading to triggering the A2 event (serving becomes worse than threshold) by the mobile. Two mobility events were specifically designed to be used to trigger the actual system change to another RAT if the inter-RAT measurement had already started:

- B1 (the inter-RAT neighbor becomes better than threshold) commonly used when the UE must leave the LTE regardless of the serving cell conditions, for instance, when the CS Fallback or the inter-RAT load balancing procedure is triggered;
- B2 (the serving becomes worse than threshold1 and inter-RAT neighbor becomes better than threshold2) applicable for coverage-based handover incl. Single Radio Voice Continuity (SRVCC) [22].

In most cases, selection of the target cell is based on signal strength, however, the criterion based on signal quality is also applicable. Release10-capable MS can optionally report both

UTRA CPICH RSCP and Ec/N0, hence the PS handover procedure can be performed towards a cell with both good signal strength and quality[18] [22]. Once the decision about PS handover to target RAT is made by the eNodeB, the needed network resources on the target cell are reserved in advance in the handover initiation phase. This is the principal feature of PS handover [12]. Only after establishing the resources in the target network, the Mobility from E-UTRA Command message is sent to the mobile and the actual handover takes place.

12.8.1.6 Cell Change Order to GSM

Apart from the PS handover, there are two other means to change the network from E-UTRAN to GSM in RRC_CONNECTED mode: cell change order and RRC connection release with redirection. The former is an embodiment of the network-controlled cell reselection procedure. Cell change order may be triggered without prior measurements of GSM cells [22]. This option is especially applicable for 1:1 deployment in the same band where GSM and LTE cells are collocated. If such a measurement procedure is, however, configured, the list of GSM cells (i.e., ARFCNs related to the BCCH of the potential GSM target cells) to be measured prior to the possible RAT change is delivered to the mobile. Similar to measurements of the WCDMA network, an A2 event is typically used to trigger the measurements of GSM cells. Generally, measurements of inter-RAT layers – especially GSM – should be triggered by the network early enough in order to collect the signal strength samples for GSM cells and decode the BSIC of these cells while still being in LTE coverage. However, if measurement gaps are needed for the measurement campaign due to UE capability, they have to be scheduled by the network potentially at the cost of the user perceived throughput – during the measurement gap the mobile does not receive or transmit any user data. If the signal strength of the serving cell has increased above the given threshold during the measurement campaign (A1 event), measurements of GSM cells are stopped.

Due to the characteristics of the GSM measurement process performed by the mobile (refer to [26] for further details,) it is important to keep the list of 2G cells to be measured by the UE as short as possible. Too long a list may unnecessarily delay the reselection process since measurement gaps are shared in concurrent mode between measurement campaigns related to various RATs if they are triggered by the network. As a consequence of this fact, the time needed for example, to perform the BSIC decoding of the GSM cell is increasing together, with an increasing number of UTRAN carriers that should be measured prior to the PS handover to WCDMA [26]. Note also that an excessive interference level in the GSM network may reduce the ability of the UE to decode the BSIC of the given GSM cell correctly. On the other hand, too restrictive a list may lead to a suboptimal Cell Change Order (CCO) decision where the mobile will be forced to reselect an imperfect cell from the radio condition's point of view, while better cells would not be measured. Moreover, if there is no dedicated BCCH and TCH band defined in the spectrum used by the operator, that is, the given frequency could belong to the BCCH layer in one cluster and the TCH in another, it is crucial to configure this list properly that is, to include only ARFCNs used by BCCH in the given area.

B1/B2-related thresholds (described in Section 12.8.1.5) and corresponding timers could be set separately for different sets of ARFCN frequencies. This means that effective prioritization between various GSM cells could be done. One of the optimization strategies of the inter-RAT

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[18] 3GPP Rel.10 introduces the support of reporting both UTRA CPICH RSCP and Ec/N0 in a Measurement Report and eNodeB can process both values during target cell selection [13].

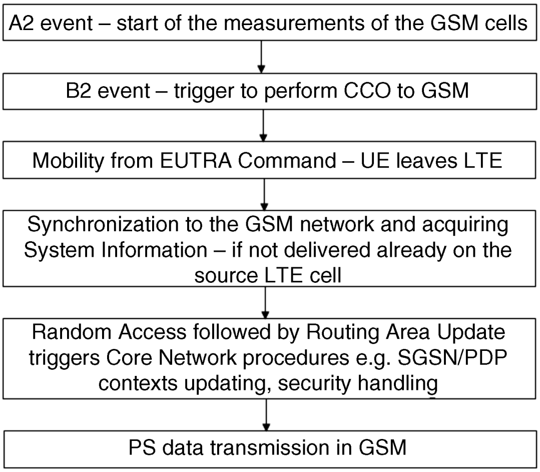
A2 event – start of the measurements of the GSM cells
B2 event – trigger to perform CCO to GSM
Mobility from EUTRA Command – UE leaves LTE
Synchronization to the GSM network and acquiring System Information – if not delivered already on the source LTE cell
Random Access followed by Routing Area Update triggers Core Network procedures e.g. SGSN/PDP contexts updating, security handling
PS data transmission in GSM

Figure 12.58 Cell Change Order to GSM procedure.

procedures could be to route the traffic from the E-UTRA to the GSM cells (layers) where more advanced PS features are available such as EGPRS, Downlink Dual Carrier or EGPRS-2 to limit the performance gap between the source and the target system from the throughput as well as the delay point of view. For a brief description of these features, refer to Section 12.3.6. Note, however, that if the measurements are not scheduled before the actual inter-RAT cell change, other mobility events like, for example, A2 (serving becomes worse than threshold) may be also employed to trigger the actual cell change.

Once the decision to perform the CCO is made by eNodeB, one specific target GERAN cell is included in the Mobility from the E-UTRA Command message sent to the mobile (with purpose set to "cellChangeOrder" not "handover" as is the case for PS handover). Note that eNodeB may filter the target cell list according to some additional criteria like blacklisting of cells or UE capability – hence, not necessarily the strongest reported GSM cell will be a final target for the CCO procedure. This network control over the traffic routing is one of the advantages of employing the Cell Change Order procedure to change the network from LTE to GERAN – instead of RRC connection release with redirection. A typical sequence of events for Cell Change Order to GSM procedure for the mobile that does not support CS services is presented in Figure 12.58.

The network could send System Information assistance data in the Mobility from the E-UTRA Command message that is, the set of SI related to the target cell. The set of SI for inter-RAT change assistance is not standardized by 3GPP but commonly SI1, SI3 and SI13 could be transmitted [23] as in the intra-GSM case. These SI the mobile would have to acquire before performing the packet access or entering the packet transfer mode [23] if they were not provided in the source cell. The actual content of SI of GSM cells could be either retrieved with the help of RIM or made available in the source eNodeB in automatic or manual way (via the O&M process).

On receiving Mobility from EUTRA Command, the UE is allowed to leave LTE without previously sending any acknowledgment message. Note that if S3/S4 interfaces are not deployed in the network, the legacy Gn interface could be used to connect the 2G/3G SGSN with LTE Core (3GPP 23.401 annex D [12]). In such a scenario, from the point of view of the legacy 2G/3G SGSN, the MME will be perceived as another SGSN while the PGW will be treated like GGSN during the Cell Change Order procedure. After leaving the LTE network, the mobile has to tune to GSM frequency, synchronize to the network and listen to the System Information (if needed). The sending of the SI already inside Mobility from EUTRA Command allows the cell outage time to be reduced– even 1 second could be gained if NACC is employed together with CCO, since there is no need to read the SI after camping on GSM cell. If all the necessary messages are known to the UE, the Channel Request on RACH is sent by the mobile in order to have the radio resources granted to perform the Location Area Update (LAU) if the mobile is CS-capable. Subsequently, the random access procedure has to be repeated in order to perform a Routing Area Update. If the Gs interface between the MSC and the SGSN is available and a Combined LA/RA update is possible, this time could be reduced by approximately 2 seconds – since the Location Area Update message is embedded in the Routing Area Update (RAU) message and there is no need to perform the separate LAU. The expected overall time needed to perform CCO from LTE to GSM (i.e., between receiving Mobility from EUTRA Command and sending the RAU Complete in GSM) may be even longer than a few seconds. If, for any reason, the UE fails to connect to the GSM network and the T304 timer expires, the value of which is provided inside Mobility from EUTRA Command, the UE sends an RRC Connection Reestablishment Request message with cause “Handover failure” in order to try to revert back to LTE.

12.8.1.7 RRC Connection Release with Redirection

If the RRC Connection Release with Redirection is employed, the UE is ordered to enter the RRC_IDLE state and attempt to camp on a cell in the indicated RAT via the cell selection procedure [19]. The RRC connection release with redirection to WCDMA or GSM should be used as a kind of last resort, to be applied if there is no reasonable means to keep the connection inside the LTE network and the orthodox inter-RAT mobility procedures were not triggered due to lack of support for certain functionality on either the mobile or the network side or due to other reasons, for example, a rapid field drop.

Usually an A2 event (i.e., a serving cell becomes worse than threshold) is used to trigger the actual cell change, either based on serving cell RSRP or RSRQ. Having both RSRP and RSRQ criterion, UE can be redirected to another LTE frequency layer or a different RAT to avoid performance degradation not only due to poor coverage but also due to extensive interference. Redirection targets are indicated in the RRC Connection Release message [22] where the UTRAN carrier frequency or sequence of GSM carrier frequencies is included.

Originally, in the 3GPP specifications [22], the network may assist the UE by providing certain System Information of the target GSM cell only in the case of Cell Changer Order, enhanced with Network Assisted Cell Change procedure. However, mostly to enhance the CS Fallback procedure that may also be based on the redirection procedure (cf. Section 12.8.2.1.3), the possibility of providing the SI assistance data was extended in 3GPP Release 9 also to RRC connection release with the redirection case. Since the exact GSM cell the mobile will redirect to is not known in advance during the redirection procedures, instead of delivering System Information of a single GSM cell, a set of SI related to up to 32 GSM cells may be provided in such a case – together with their ARFCN and BSIC (called Physical Cell ID in E-UTRAN specifications). Once the pair of ARFCN and BSIC matches with the GSM cell that the mobile redirects to, an appropriate SI could be used to speed up the access procedure to the new cell.

The RRC connection release with redirection could be also used to move the UE out of the WCDMA network. In the "Redirection info" in the RRC Connection Release message sequence of GSM or E-UTRAN frequencies could be given [21] – together with some supplementary information such as the BSIC of the GSM cell or a list of blacklisted cells for the LTE network. After receiving this message, the mobile tries to camp on any of the applicable cells. As an additional option, inter-RAT redirection information could also be included by the network in the RRC Connection Reject message – sent as the network response to the RRC Connection Request. Such a procedure could be triggered if, due to some reason, the requested RRC connection could not be accepted in UTRAN.

The counterpart procedure is also available in the GSM network. Once "Cell selection indicator after release of all TCH and SDCCH" is included in the Channel Release message, the mobile uses this information in the cell selection algorithm – information about the desired target UTRAN as well as the E-UTRAN cells could be included there [14].

12.8.1.8 Summary

An example relationship between various event thresholds mentioned in Section 12.8.1 is presented in Figure 12.59. For simplicity, LTE RSRQ or WCDMA CPICH EcNo triggered events are not presented.

Typically, the measurements and triggers of the actual leaving of the LTE network are scheduled in a sequential manner and the availability of a more favorable layer from the inter-RAT strategy point of view is checked first. In Figure 12.59 higher priority was assigned to WCDMA target cells in comparison to GSM cells. If both cell change order and

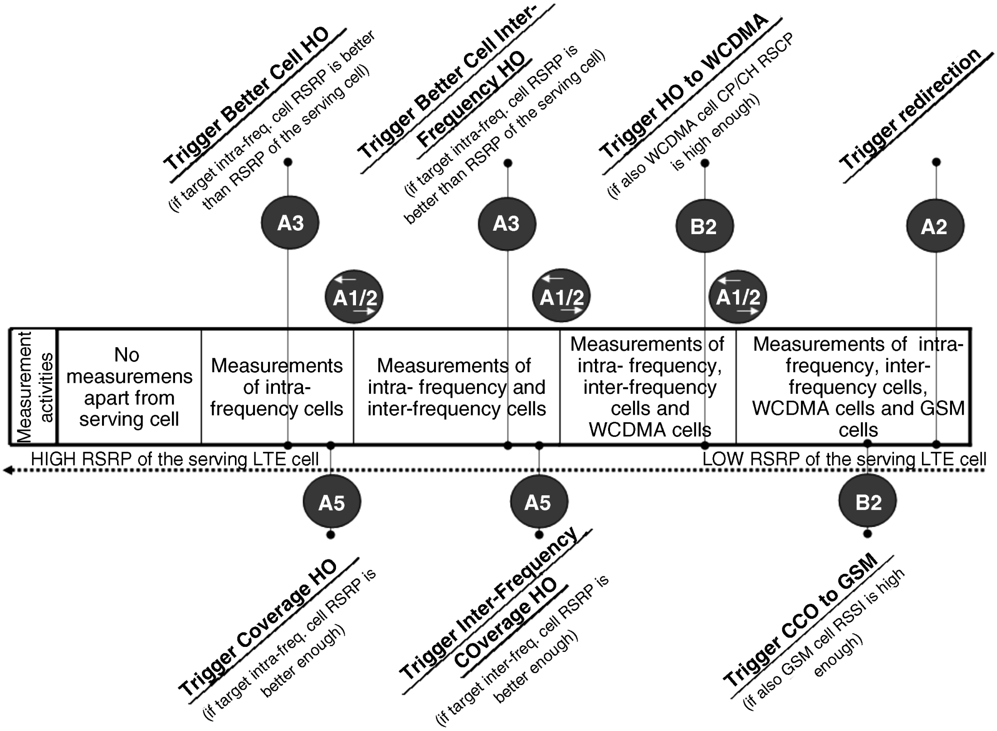
Trigger Better Cell HO
(if target intra-freq. cell RSRP is better than RSRP of the serving cell)
Trigger Better Cell Inter-Frequency HO
(if target intra-freq. cell RSRP is better than RSRP of the serving cell)
Trigger HO to WCDMA
(if also WCDMA cell CP/CH RSCP is high enough)
Trigger redirection
A3
A3
B2
A2
A1/2
A1/2
A1/2
Measurement activities
No measuremens apart from serving cell
Measurements of intra-frequency cells
Measurements of intra- frequency and inter-frequency cells
Measurements of intra- frequency, inter-frequency cells and WCDMA cells
Measurements of intra-frequency, inter-frequency cells, WCDMA cells and GSM cells
HIGH RSRP of the serving LTE cell
LOW RSRP of the serving LTE cell
A5
A5
B2
Trigger Coverage HO
(if target intra-freq. cell RSRP is better enough)
Trigger Inter-Frequency COverage HO
(if target inter-freq. cell RSRP is better enough)
Trigger CCO to GSM
(if also GSM cell RSSI is high enough)

Figure 12.59 Various event thresholds – summary.

RRC connection release with redirection are supposed to be used for the inter-RAT mobility towards GSM, usually the cell change order related measurements should be started first. A connection release with redirection may be useful if a rapid drop of RSRP occurs once, for example, if the LTE coverage is ending. Note that the differentiation between various potential target cells for intra-RAT as well as inter-RAT mobility from E-UTRAN could be applied not only via the appropriate setting of certain thresholds but also the time to trigger values delivered to the mobile.

In order to assure consistent behavior with respect to interworking functionalities, the network planning and optimization has to be performed jointly for all involved RATs. For instance, in the case of GSM-LTE interworking, the following alignments may be considered:

- between idle and dedicated mode inside LTE, for example, the relationship between the RSRP leading to the inter-RAT reselection from LTE to GSM and the CCO-specific threshold;
- between the minimum 2G signal strength requirements related to access to the GSM cell and the CCO parameters in order not to try to force the reselection to too weak a GSM cell;
- between LTE and GSM reselection parameters that govern the network change from GSM to LTE (via common reselection process based on the absolute priorities as described in Section 12.8.1.1) to avoid the ping-pong effect
- between the CCO-related parameters and the inter-system reselection parameters from GSM to LTE also to avoid the ping-pong effect.

Another important aspect to be considered when analyzing inter-RAT mobility is the handling of Quality of Service during such procedures. One-to-one mapping between an EPS bearer and a PDP Context was standardized [12]. Some rules related to R99 and R8 QoS parameters were provided in 3GPP standards but the exact implementation of this mapping is, however, operator-specific. For more details regarding QoS handling, refer to [12].

12.8.2 CS Fallback

The realization of voice services in LTE that incorporates no CS domain in its architecture attracts special attention. A number of different alternatives have been developed by either 3GPP or other organizations like the VoLGA Forum. These are covered in detail in dedicated chapters throughout the book. In this section, in the context of LTE and legacy systems interworking, CS Fallback deserves special considerations. The discussion is focused on practical deployment aspects and interdependencies with data centric mechanisms.

The CS Fallback (CSFB) functionality, introduced by 3GPP in Release 8 and further enhanced in next releases, allows the operators to re-use the CS domains and the corresponding RANs of legacy networks to provide voice (and other CS services) to multimode terminals being attached to EPS. CS Fallback provides a mechanism for a service-based redirecting of CSFB-capable mobiles from E-UTRAN towards other RAT that supports CS-domain services (e.g., GERAN or UTRAN). It may be triggered by either a mobile-originated or a mobile-terminated call. The CS Fallback functionality requires that the E-UTRAN coverage is overlapped by the target RAT coverage. Furthermore, the dedicated interface between the MME of EPS and the MSC/MSC Server of CS core network is necessary for interworking procedures such as combined EPS/IMSI attach or combined Tracking Area/Location Area update. For this purpose, the so-called SGs interface has been defined [27]. Combined EPS/IMSI attach and combined TA/LA update procedures ensure that a UE is registered not only to

EPS but also to an appropriate location area of the CS domain of the underlying network so that CS services are available. To ensure the proper handling of data services during CS Fallback, cooperation between EPS and the target PS core network is necessary. The inter-system interworking architecture can be based either on the 3GPP Release 8 S3/S4 interfaces or on the pre-Release 8 Gn/Gp interfaces. It must, however, be noted that the Gn/Gp based interoperability architecture entails some modifications of particular interworking procedures, like routing and tracking area updates, data forwarding, and so on, that in turn may result in suboptimal performance from both the network's and the users' viewpoint. Details on the Gn/Gp interoperation architecture can be found in 23.401 Annex D [12].

When analyzing the CS Fallback functionality in the context of its deployment in a life network, the main focus is automatically put on the performance of voice services in terms of call set-up time. Nevertheless, activation of the CS Fallback, which by definition leads to a temporary switch-over from E-UTRAN to other RAT, may influence the performance of PS services in terms of data session interruption time and user data throughput. Furthermore, discussion of CS Fallback deployment aspects should cover not only the users' perceived quality of service topics but also those related to the impact on overall network performance. All these aspects are discussed in more detail hereafter.

12.8.2.1 Voice Performance

Since the inherent feature of the CS Fallback procedure is to force a UE to switch from E-UTRAN to CS-capable RAT, total voice call establishment time includes additional delay compared to call set-up executed directly in a given RAT. This delay depends mainly on how long it takes to redirect a UE from E-UTRAN and how quickly the CS call set-up procedure can be executed in the target cell. These delays, in turn, are strongly determined by the target RAT technology as well as mobility management mechanisms which CS Fallback itself is based on. There are three different mechanisms that can be used to fall back the UE to other RAT, namely: inter-RAT PS handover, the cell change order (including Network Assisted Cell Change), and the RRC connection release with redirection [27].

12.8.2.1.1 CS Fallback via inter-RAT PS Handover

CS Fallback via inter-RAT PS handover is the most advanced option and most reliable due to resource reservation in the target RAT. In this CS Fallback realization, whenever a UE needs to be moved to another RAT due to a pending CS call establishment, the standard inter-RAT PS handover from E-UTRAN procedure is invoked. The target cell is determined either based on UE measurement reports or based on configuration settings only [27]. With the first option, a UE is requested to perform the target carrier measurements before leaving the LTE cell, which introduces additional delay to call set-up time. To minimize the time spent on target cells measurements, the number of target frequency carriers should be kept to the minimum, especially for GERAN layers. This additional delay could be avoided by triggering the EPS/IMSI attached terminals in the ECM-CONNECTED mode to measure and report inter-RAT neighbor cells proactively so that actual target-RAT cells measurements are available upon CS Fallback is attempted. The proactive measurement approach can be especially favorable for the MSs which do not require measurement gaps for the measurement campaign, preserving the user data throughput. With the target cell selection based on the UE measurement, current signal propagation conditions are taken into account so that the most suitable cell can be chosen. The second alternative, the so-called blind target cell selection,

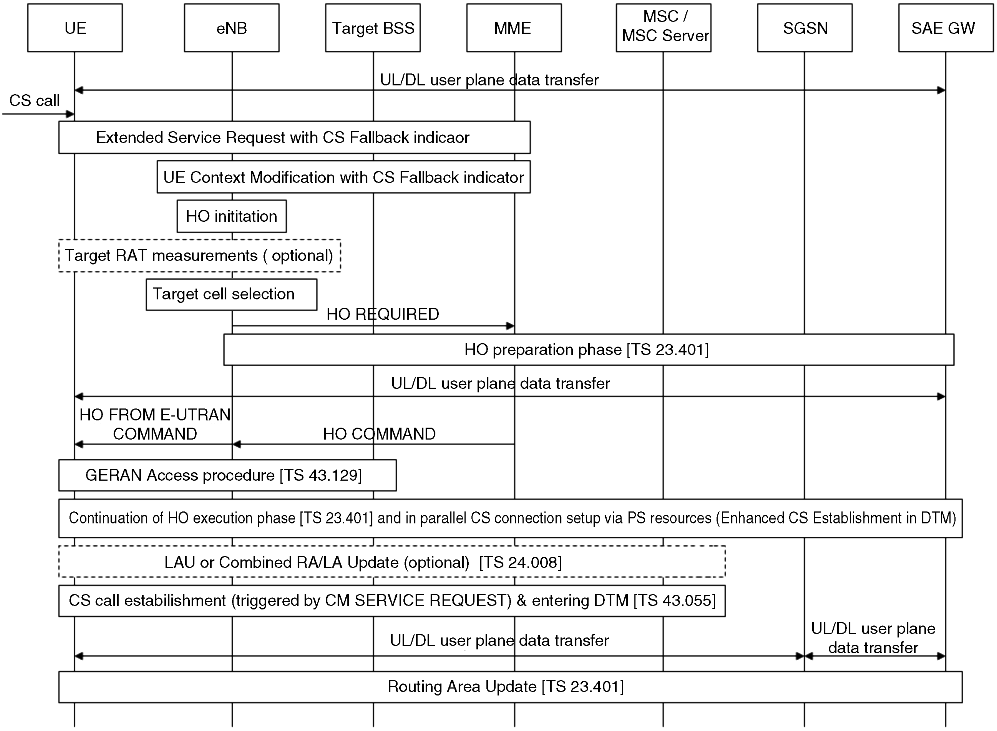
UE
eNB
Target BSS
MME
MSC / MSC Server
SGSN
SAE GW
UL/DL user plane data transfer
CS call
Extended Service Request with CS Fallback indicaor
UE Context Modification with CS Fallback indicator
HO inititation
Target RAT measurements (optional)
Target cell selection
HO REQUIRED
HO preparation phase [TS 23.401]
UL/DL user plane data transfer
HO FROM E-UTRAN COMMAND
HO COMMAND
GERAN Access procedure [TS 43.129]
Continuation of HO execution phase [TS 23.401] and in parallel CS connection setup via PS resources (Enhanced CS Establishment in DTM)
LAU or Combined RA/LA Update (optional) [TS 24.008]
CS call estabilishment (triggered by CM SERVICE REQUEST) & entering DTM [TS 43.055]
UL/DL user plane data transfer
UL/DL user plane data transfer
Routing Area Update [TS 23.401]

Figure 12.60 CS Fallback to GERAN via inter-RAT PS HO for mobile-originated call in ECM-CONNECTED state; DTM and enhanced CS establishment supported.

avoids the additional call set-up delay but can be applied only in coordinated scenarios with one-to-one overlapping between E-UTRAN and target RAT cells. The applicability of the first method is not limited to the coordinated scenario. If E-UTRAN coverage is overlapped by several target RAT layers, a prioritization mechanism can be used to prefer certain technologies or frequencies to others.

The next steps of handing over of a UE towards a selected target cell are similar to a normal inter-RAT PS handover procedure described in [12]. The main difference is that having switched to the target cell, the UE attempts to establish a CS connection. The procedure of CS call establishment follows the rules specific to the target RAT. In UTRAN, the CS call can be set up in parallel to the PS connections established upon the successful completion of the inter-RAT handover procedure without any PS session interruptions and additional voice call set-up delays. In GERAN, such a smooth establishment of CS connection can take place only if both the network and the UE support the Dual Transfer Mode and enhanced CS establishment in DTM (see [28]). In such a scenario (Figure 12.60), the CS call set-up procedure can be executed over already allocated packet resources and without leaving the packet transfer mode. If the network and the UE support DTM but not enhanced CS establishment in DTM, the CS call set-up cannot be done while in packet transfer mode. Thus voice call establishment entails the temporary intermission of ongoing PS sessions and switching to packet idle mode. Having left packet transfer mode, the UE attempts CS connection establishment via the standard random access procedure [27]. This results in longer voice call set-up times when comparing to UTRAN or GERAN with enhanced CS establishment in DTM scenarios. After successful CS call set-up, packet transfer mode can be re-established so that the PS data session is continued in parallel to the voice call. Data session interruption time is then determined by duration of the CS call set-up procedure. Upon re-entering packet transfer mode the UE performs the remaining steps of inter-RAT handover as in the standard non-CS Fallback case. Having completed voice call, the UE follows the standard mobility management procedures. Whether the UE stays in the target RAT or moves back to E-UTRAN, it depends on the parameterization of those procedures, for example, the Cell Selection Indicator information element included in Channel Release message may force the UE to reselect to E-UTRAN as soon as a suitable cell is available [14].

If either the network or the UE does not support Dual Transfer Mode, packet transfer mode set-up during inter-RAT PS handover must be left not only for the time of establishing CS connection but for the whole CS call duration. Having switched to packet idle mode, a UE triggers the CS call set-up procedure by sending channel request on random access channel [27]. The need to go through the random access procedure introduces additional delay to the voice call set-up time. Another consequence of the lack of DTM support is that all active PS sessions must be put on hold until the voice call is completed. This is realized via what is called the suspend procedure that must be triggered by the UE before requesting a dedicated traffic channel for CS call (before sending the CM Service Request with service type set to the originating call establishment or the Paging Response message). Consequently, all the remaining standard steps of the inter-RAT PS handover are abandoned. The Suspension Request message is sent by the UE to the BSC over Standalone Dedicated Control Channel (SDCCH) so that no PS resources are involved. The BSC forwards the Suspension Request to the SGSN. If the inter-RAT interworking architecture is based on the legacy Gn/Gp interfaces, upon receiving the Suspend message from the UE, the SGSN follows the intra-SGSN suspend procedure. It means that PS sessions are suspended internally within the SGSN and without any interaction with the P-GW [29]. If the inter-RAT interworking architecture is based on the S3/S4 interfaces, being triggered by the UE, the SGSN attempts the suspend procedure towards the S-GW and the P-GW. In consequence, the deactivation of GBR bearers and the suspension of non-GBR bearers are triggered. In this case, as opposed to the Gn/Gp scenario, the P-GW should discard the packets dedicated to the suspended UE [29]. When the CS connection is completed, the suspended PS sessions may be resumed via corresponding procedures described in [29]. The UE may start the resume procedure either from a legacy RAT or having switched back to E-UTRAN. Whether the UE stays in the target RAT or moves back to LTE, it depends on the parameterization of the existing inter-RAT mobility management mechanisms. With the appropriate configuration of those mechanisms, the UE may be forced to reselect back to LTE as soon as a suitable cell can be found.

Regardless of the target RAT type and capability, the CS call set-up procedure may need to be preceded by location area update. The LAU procedure is performed by the UE if the Location Area Identity (LAI) of the new cell towards which it has been handed over differs from the one stored in the UE [27]. This procedure introduces additional delay to voice call set-up time and hence to minimize total delay, it is crucial to ensure that the LAI stored by the UE is up-to-date and corresponds to the LAI of the target cell. Whether the Location Area in which the UE is registered to, as a result of the combined EPS/IMSI attach or the combined TA/LA update procedure, matches the LA of the target cell depends on the tracking area and the location area plans as well as algorithms of tracking area list management implemented in the MME. To minimize the impact of the LAI mismatch on the CS Fallback performance, the mechanism based on triggering location area update just after the UE is handed over to the UTRAN/GERAN cell and without waiting for current LAI information can be considered. This solution shortens the call set-up time for those terminals that are not registered in the correct LA but introduces unnecessary delay for those registered in the proper LA. Hence it is kind of trade-off and is worth considering if the risk of LAI mismatch is relatively high due to, for example, lack of alignment of TA and LA plans. Location area update-related aspects are further discussed in Section 12.8.2.1.4.

Discussing CS Fallback via inter-RAT PS handover, it should be noted that this solution requires the standard PS handover functionality to be supported by both the target RAT and the terminal. This, in practice, narrows down the usability of CS Fallback via the inter-RAT PS handover to scenarios in which the target RAT is UTRAN and not GERAN, and if this is the case, the PS handover is rather rarely deployed. Furthermore, if the CS Fallback is triggered when a UE is in ECM-IDLE mode, the inter-RAT handover mechanism may not be an efficient means of CS Fallback realization since there is no real need to establish PS connections in the target RAT. Hence, other inter-RAT mobility procedures, discussed in subsequent part of this section, may be regarded as more practical ones.

12.8.2.1.2 CS Fallback via Cell Change Order

In scenarios where the inter-RAT PS handover is not practicable and the target RAT is GERAN, the CS Fallback may be based on the inter-RAT cell change order (CCO) mechanism. In such a case, each mobile-originated or mobile-terminated call triggers the CCO procedure. As in the standard CCO case, the CS Fallback target cell must be provided to the UE. Target cell selection can be based either on UE measurement reports or on configuration settings only. The advantages and disadvantages of these two alternatives are analogous to those discussed for a CS Fallback via the inter-RAT PS handover scenario. In the case of measurement-based target cell determination, the number of frequency carriers to be measured should be kept to the minimum to avoid long delays introduced by this step to the total CS call establishment time. Furthermore, if the E-UTRAN coverage is overlapped by more than one GERAN layer, some prioritization mechanisms can be used to prefer certain frequencies to others.

Having switched to the target cell, the UE must acquire a defined minimum set of system information before it is allowed to attempt the initial access procedure which results in additional delay in call set-up time. By employing the Network Assisted Cell Change (NACC) feature, the UE may be provided with target cell system information while it is still in LTE cell. The UE may use this information when accessing the target cell and hence avoid scanning the BCCH for system information. If not all the necessary system information has been delivered to the UE, it still needs to acquire missing system information before initiating the random access procedure in the new cell. Further discussion on CCO and NACC is provided in Section 12.8.1.6. Having collected all the necessary system information, the UE attempts to establish a CS signaling connection so that the voice call set-up procedure can be continued. Here, similar to the case of CS Fallback via the inter-RAT PS handover, the call set-up procedure may need to be preceded by the location area update. Thus the discussion on LAU aspects provided hereafter is relevant also to CS Fallback via the CCO scenario. Furthermore, as during a normal CCO procedure, the routing area update must be performed by the UE as soon as possible. Whether the RAU procedure is performed in parallel to CS connection, it depends on the DTM capability of the UE and the network. If the DTM is supported by both the network and the UE, the RAU can be realized over the CS signaling channel using GPRS Transparent Transport Protocol (GTTP) and without the need for a PS connection establishment. Subsequently, the UE may enter the DTM mode so that the CS and PS services are available simultaneously (Figure 12.61). Having successfully completed the RAU procedure, the SGSN asks the MME (via either the S3 or the Gn interface) about the EPS bearers of the UE so that the

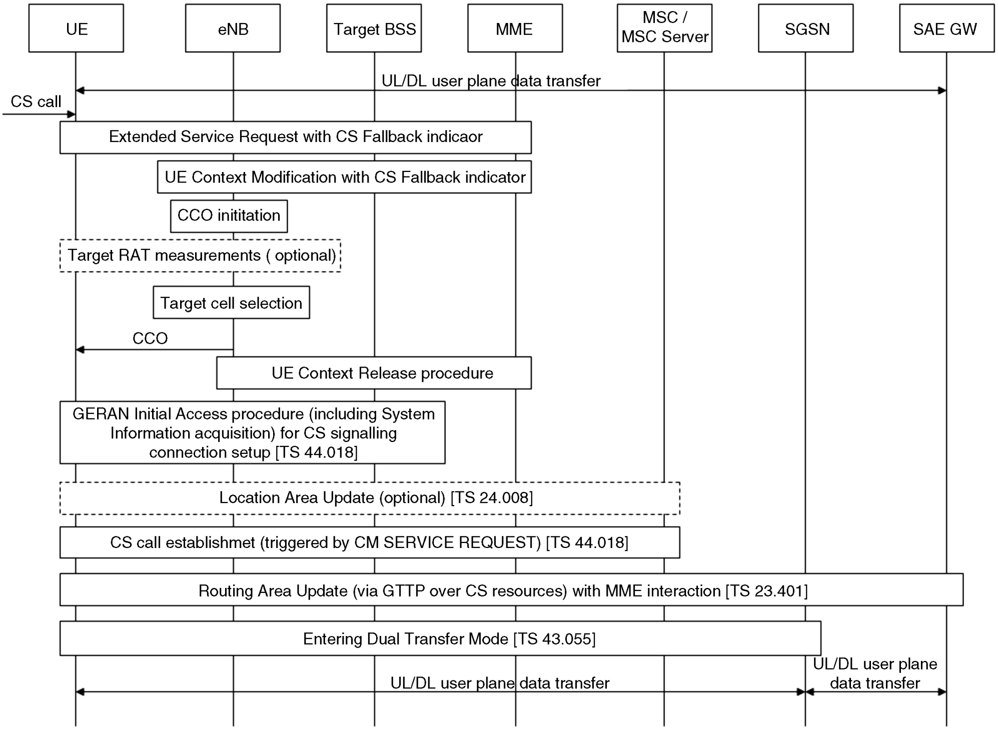
UE
eNB
Target BSS
MME
MSC /
MSC Server
SGSN
SAE GW
UL/DL user plane data transfer
CS call
Extended Service Request with CS Fallback indicaor
UE Context Modification with CS Fallback indicator
CCO inititation
Target RAT measurements (optional)
Target cell selection
CCO
UE Context Release procedure
GERAN Initial Access procedure (including System Information acquisition) for CS signalling connection setup [TS 44.018]
Location Area Update (optional) [TS 24.008]
CS call establishmet (triggered by CM SERVICE REQUEST) [TS 44.018]
Routing Area Update (via GTTP over CS resources) with MME interaction [TS 23.401]
Entering Dual Transfer Mode [TS 43.055]
UL/DL user plane data transfer
UL/DL user plane data transfer

Figure 12.61 CS Fallback to GERAN via CCO without NACC for mobile-originated call in ECM-CONNECTED state; DTM supported.

LTE-originated data sessions can be continued using GERAN PS resources. The data session interruption time is, in such a scenario, dependent mainly on two factors, that is, the time a UE needs to tune to the indicated frequency and to acquire the necessary system information as well as the duration of the RAU procedure. If the UE had no ongoing session in the EPS when the CSFB was triggered, no PS resources are assigned to the UE in the GERAN cell. Upon completion of the CS call, the UE starts to follow standard mobility management procedures. To force reselection towards LTE cells, the appropriate parameterization that favors E-UTRAN cells over other RAT cells should be applied.

If either the UE or the network does not support DTM, the RAU procedure cannot be realized over the CS signaling links and hence requires dedicated PS connection to be set up. Consequently routing area update and any PS session establishment must be put on hold until the CS call is completed. Due to this temporary PS services unavailability, the UE must trigger the suspend procedure [29] before continuing with voice call set-up. The Suspension Request message is transferred over the CS signaling link (no need for PS connection set-up) to the BSC that in turn forwards this message to the SGSN. The SGSN triggers the suspend procedure towards MME via either S3 or Gn IF. Since the MME may be unable to retrieve the full GUTI based on the combination of P-TMSI and RAI received from the SGSN and hence may not be able to determine which UE context should be suspended, in Release 9, the 3GPP has defined the mechanism for triggering suspension internally within the EPS upon ordering the UE to fall back to the non-DTM environment [27]. Having triggered the Suspend message the UE may finally continue with the CS call set-up by sending either the CM Service Request (with the service type set to originating call establishment) or the Paging Response via the SDCCH channel. As soon as a voice call is terminated, the UE may start the resume procedure by performing RAU if it remains in GERAN or TAU if it switches back to LTE. In such a scenario, the main contributor to the total data session interruption time is the voice call duration.

12.8.2.1.3 CS Fallback via:RRC Connection Release with Redirection

In scenarios where neither inter-RAT PS handover nor inter-RAT cell change order is applicable, the only option for the CS Fallback realization is the RRC connection release with redirection. This solution is applicable to any target RAT. In the case of the RRC connection release with redirection, the UE is provided with the list of frequency carriers of potential target cells and not with the one exact cell towards which fallback should be performed. This realization does not require any target RAT measurements to be performed before leaving an LTE cell. The list of potential targets can be determined based on the configuration parameters and the UE capabilities only. However, if any target RAT measurements (e.g., periodic measurements) are available upon triggering the CS Fallback, they may be re-used by the algorithm of targets list generation. Such an approach, on the one hand, allows the UE to leave the LTE cell as soon as the CS Fallback is triggered and without any delay caused by the target RAT measurements. On the other hand, this entails the UE to scan the indicated spectrum and select a suitable cell in the target RAT by itself. This time spent on searching for a suitable target cell is of the main concern in the context of voice call set-up time. To keep this time at a minimum, frequency carriers indicated to the UE should be optimized so that they correspond to the most suitable target cells. Having selected the target cell, the UE must, analogously to CS Fallback via the CCO scenario, acquire the necessary system information before it is allowed to start the random access procedure. Resulting additional delay of the voice call establishment can then be avoided in two ways: either with the one introduced in Release 7 – Deferred Measurement Control Reading which allows skipping SIB11/SIB11bis and SIB12 reading before RACH access, or with the help of Release 9 enhancement – Multi Cell System Information[19] [21, 27]. This functionality enhances the RRC connection release with the redirection mechanism so that a UE may be provided additionally with the physical identities and system information corresponding to potential target cells. The first option can reduce the call set-up time by hundreds of milliseconds. The second can speed up the procedure even by few seconds, depending on the target RAT and the actual size of System Information. However, SI must be available in the eNodeB. The most efficient way to acquire System Information from the target node is to use the RAN Information Management (RIM) functionality. RIM provides the content of GERAN System Information (SI1, SI3, SI13) and the UTRAN ones (MIB, SI1, SI3, SI5, SI7).[20] The maintenance of the System Information is also improved with RIM since it is automatically updated in the eNodeB upon changes in the target node [21,30]. Having selected one of the cells for which the necessary system information has been acquired before leaving the LTE cell, the UE may start the CS call set-up procedure immediately. The call establishment procedure itself is executed according to the standard rules specific to a given RAT. In Figure 12.62 the example of a CS Fallback

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[19] Deferred Measurement Control Reading is only applicable for UTRAN whereas provisioning of System Information of potential target cells can be used for both GERAN and UTRAN.

[20] Apart from the listed System Information for UTRAN, RIM can also optionally provide the content of the System Information SI11, SI11bis, SI12, SI22 and Scheduling Blocks (SysInfoTypeSB1, SysInfoTypeSB2) [14].

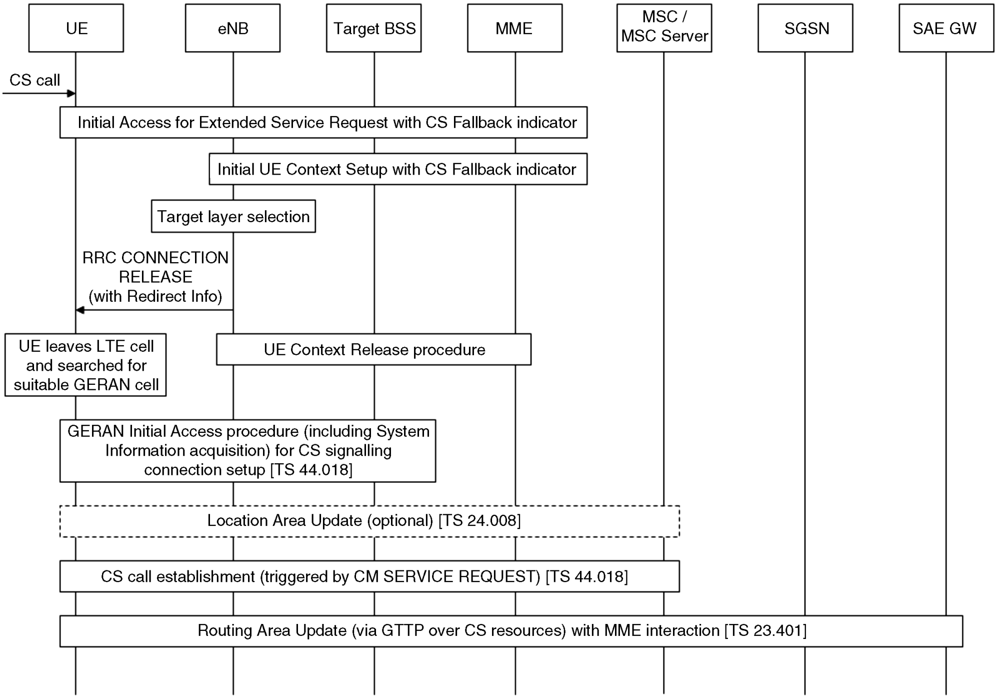
UE
eNB
Target BSS
MME
MSC / MSC Server
SGSN
SAE GW
CS call
Initial Access for Extended Service Request with CS Fallback indicator
Initial UE Context Setup with CS Fallback indicator
Target layer selection
RRC CONNECTION RELEASE (with Redirect Info)
UE leaves LTE cell and searched for suitable GERAN cell
UE Context Release procedure
GERAN Initial Access procedure (including System Information acquisition) for CS signalling connection setup [TS 44.018]
Location Area Update (optional) [TS 24.008]
CS call establishment (triggered by CM SERVICE REQUEST) [TS 44.018]
Routing Area Update (via GTTP over CS resources) with MME interaction [TS 23.401]

Figure 12.62 CS Fallback to GERAN via RRC connection release with redirection for mobile-originated call in ECM-IDLE state; DTM supported; Multi Cell System Information not supported.

procedure to GERAN is presented. If the UE-stored LAI does not match the LAI of the new cell, the voice call set-up must be preceded by the location area update. Consequently, the voice call establishment time may be protracted. Discussion on how to minimize the probability of the need for LAU is provided in the subsequent part of this section. In parallel to the CS domain activities, a UE should also perform a routing area update. In UTRAN and Dual Transfer Mode GERAN scenarios, there are no issues with executing RAU in parallel to CS activities. Consequently, the LTE-originated data sessions (if any) can be continued in the target RAT concurrent with the voice call. Data session interruption time is, in such a scenario, determined mainly by the time of searching for the suitable target cell and acquiring the necessary system information as well as the RAU execution time.

In the non-DTM GERAN case, RAU and any PS data session set-up require the CS connection to be released and hence can be performed only if the voice call is completed. This entails the suspend procedure to be triggered by the UE before CM Service Request (with the service type set to the originating call establishment) or a Paging Response can be sent. The suspend procedure is executed in the same way as in the CF Fallback via the CCO case. Furthermore, due to P-TMSI and RAI to GUTI mapping issues, the mechanism for triggering suspension internally within EPS upon redirecting UE to non-DTM capable GERAN cell may be helpful. The PS session resume procedure that can be attempted, when the CS call is finished, is triggered by either RAU if the UE remains in GERAN or TAU if the UE switches back to LTE. In this scenario, the potential data session interruption time depends not only on how quickly the UE searches for target cell and acquires system information but also on the voice call duration. As in other CS Fallback scenarios, having completed a CS call, a UE follows the standard mobility management procedures and by their appropriate configurations it may be forced to switch back to LTE as soon as a suitable cell is found.

12.8.2.1.4 Interdependencies with Fundamental Procedures

The target RAT type and the mechanisms via which CS Fallback is realized are not the only factors influencing the voice call set-up time. The performance of the CS Fallback procedure also depends on the EPS Connection Management (ECM) state of the UE. CS Fallback may be triggered (by a UE or a network) in either the ECM-IDLE or ECM-CONNECTED mode. If CS Fallback is attempted while a UE is in ECM-IDLE mode, additional call set-up delay must be considered since the UE needs to switch to ECM-CONNECTED mode. This transition is realized via standard Initial Access procedure defined in [12].

Another aspect that should be discussed in the context of the CS Fallback execution time is the paging procedure. As an intrinsic feature of a mobile-terminated call, CS paging must be invoked regardless of the ECM state. An EPS/IMSI attached UE is paged for the incoming call in the RAT it is currently camped on. Without Idle Mode Signaling Reduction (ISR), a CS Fallback-capable UE must always perform a location and routing area update when reselecting from E-UTRAN to other RAT so that the MSC/VLR knows where a certain UE should be paged. Knowing the RAT a UE is camping on, the MSC/VLR pages this UE either directly in managed RAT or via MME in E-UTRAN. If ISR is active a UE can reselect between registered areas without executing tracking, routing and location area update procedures (see Section 12.8.4). Consequently, the MSC/VLR is not able to unequivocally determine whether a UE is currently camped on an E-UTRAN or UTRAN or GERAN cell. Therefore, the MSC/VLR sends a paging message via the SGs interface to the MME that in turn handles the paging accordingly. If the UE is in the ECM-CONNECTED state, the MME triggers paging in the serving cell as in the normal case. If the UE is in the ECM-IDLE state, the MME pages the UE in all the tracking areas the UE is registered to and forwards a paging message via the S3 interface to the associated (via ISR mechanism) SGSN that in turn initiates paging in the routing area which the UE is registered [27]. Such a mechanism guarantees that a UE will be paged for a mobile-terminated call even if the location area update is skipped due to ISR. On the other hand, such an extended paging route may introduce an additional delay in voice call set-up time.

As already mentioned, one of the factors affecting the CS Fallback call set-up time (regardless of the actual fallback mechanism) is the potential need for a location area update preceding the voice call establishment. To optimize the CS Fallback performance and minimize the necessity of location area updates that are obligatory if the UE stored Location Area Identity (LAI) does not match the actual LAI of the new cell, planning of tracking and location area boundaries should be reconsidered. Since vLAI stored by the UE is the one that UE is registered to via the combined EPS/IMSI attach or combined TA/LA update, it is essential that UE executes tracking updates every time the underlying location area is changed. If there were no concept of tracking area list, the straightforward solution would be to align the boundaries of selected tracking areas in LTE with the boundaries of the location areas in the target RAT. Nevertheless, with the concept of a tracking area list, a terminal can be registered to multiple tracking areas and therefore does not perform a combined TA/LA update every time it crosses the TA boundary. In this context, apart from the alignment of TA and LA boundaries, some enhancements of algorithms for tracking area lists handling in MME could be considered so that the tracking area list indicated to the UE does not contain tracking areas spread over more than one location area. If the tracking area list covers multiple location areas, the UE might not be provided with the actual LAI of the target cell before leaving the LTE cell which in turn will result in a longer call set-up time in the target RAT. An analogous issue with the matching of the location area identities may be encountered in scenarios where the tracking area covers the location area boundary. Such a configuration may result in the ambiguity of TAI-to-LAI mapping tables managed by the MME and used for the purpose of combined EPS/IMSI attach and combined TA/LA update. Consequently terminals may be registered, starting from the combined EPS/IMSI attach procedure, in a location area different from the location area of the cell selected as CS Fallback target. It must be noted, however, that alignment of the TA and LA boundaries and LA-aware tracking area list handling may lead to non-optimal tracking area management and consequently to an increase in the signaling load in LTE. To countermeasure this effect, readjustment of cell reselection parameters could be considered. In scenarios where the LAI mismatch is unavoidable, the impact of LAU on the CS Fallback performance may be minimized by configuring the MSC to reduce the frequency of Authentication, TMSI reallocation and Identity check for terminals that are EPS/IMSI attached via the SGs interface so that the LAU is speeded up.

Another important aspect that must be considered in the context of minimizing the necessity of location area updates preceding the CS call set-up is providing SGs connectivity between proper MMEs and MSCs/MSC Servers. In other words, MMEs and MSCs/MSC Servers that serve a given geographical area must be connected to each other. Furthermore, TAI-to-LAI-to-MSC/VLR mapping tables based on which the MME derives the LAI and VLR number must be properly configured in the MME. Otherwise, it may happen that a UE falls back to the cell that is served by the MSC/MSC Server which a UE is not registered in and hence the CS connection establishment must be delayed until a successful LAU completion.

12.8.2.2 Data Performance

As already mentioned, impact on the performance of PS services is, besides the voice call set-up time issue, another important aspect of the CS Fallback deployment in a life network. This, however, is valid only in case of the CS Fallbacks triggered while a UE is in the ECM-CONNECTED state (in the ECM-IDLE mode there is no ongoing data session). In this context, the data session interruption time and temporary degradation of data throughput are of the main interests. How much the users' perceived quality of service is affected depends on the CS Fallback mechanism and the target RAT technology. PS service interruption aspects, including suspend and resume procedures, have already been discussed along with voice call set-up delay topics. The impact of CS Fallback on user data throughput may be twofold. First, if the CS Fallback is realized via the inter-RAT PS handover or cell change order, a UE may be requested to measure the target RAT carrier frequencies before leaving the LTE cell. This affects the performance of ongoing data transfers, since during inter-RAT measurements a UE cannot be scheduled with any data and it cannot transmit in the uplink – the so-called inter-RAT measurement gaps must be applied (unless a UE is a dual-radio terminal). This effect can be avoided by applying, if possible, the blind cell selection discussed in previous sections. The situation is different in the case of CS Fallback via the RRC connection release with redirection, since in such a case no target RAT measurements are needed before leaving the LTE cell regardless of the network deployment scenario. This, on one hand, does not deteriorate the user data throughputs when still in LTE cell but, on the other hand, it increases the data session interruption time. The other aspect that should be considered in the context of the influence of

CS Fallback on user data throughput is related to differences in data rates offered by E-UTRAN and target RAT. The higher the differences are, the more the perceptible degradation of user data throughput may be expected. Furthermore, insufficient performance of the target system may result even in the dropping of data sessions running originally over guaranteed bit rate EPS bearers. In this context, target RAT specific enhancements that aim at minimizing the performance gap, like those discussed in Section 12.3.6, can be considered.

12.8.2.3 Impact on the Overall Network Performance

Performance of the CS Fallback functionality may be analyzed not only from the users' perspective, as in previous sections, but also from the network viewpoint. When deploying CS Fallback in their networks, the operators may wonder if and how the overall performance of LTE and underlying target systems may be affected. Since CS Fallback re-uses some fundamental procedures like, for example, paging, initial access with NAS signaling, UE context set-up/modification/release, RRC connection release with redirection, the increase of signaling traffic on radio and S1-MME interfaces may be expected. Furthermore, signaling load on S3/S4 or Gn/Gp interfaces may grow as well, especially in scenarios with high use of the inter-RAT PS handover mechanism. How much the signaling traffic will increase depends on the CS Fallback usage ratio. With relatively low usage of this feature, its impact on the overall network performance may be hardly noticeable. From the target RAT point of view, CS Fallback activation may result mainly in an increase in the CS call set-up related signaling load and the CS traffic itself. If the target RAT is UTRAN or DTM-capable GERAN, the growth of the PS traffic and the corresponding signaling may be observed as well. Furthermore, the increase of the number of location and routing area update procedures and related signaling may be expected. The impact of CS Fallback on the target system performance depends on how much additional traffic is offered to the target RAT as a consequence of the CS Fallback activation. The lower this additional traffic is, the less noticeable is the influence of CS Fallback on the target system.

12.8.3 Single Radio Voice Call Continuity

In the discussion on voice-related inter-system interworking aspects, a few words should be spent also on the Single Radio Voice Call Continuity (SRVCC) feature. Standardized in 3GPP Release 8 and further enhanced in next releases, the SRVCC functionality complements the IMS-based Voice over LTE solution by introducing a mechanism for transferring the IMS anchored voice calls from E-UTRAN to the CS capable RAT. Hence service continuity may be sustained in scenarios with non-continuous E-UTRAN coverage supported by the UTRAN and/or GERAN one. SRVCC is an inter-RAT PS-to-CS handover that involves both radio access and core networks interactions. The SRVCC handover is applicable to voice-related EPS bearers only, with more stringent requirements for service interruption time than regular inter-RAT PS handover [31]. Non-voice-related EPS bearers including PS bearers related to video call, must be handled with the inter-RAT PS handover mechanisms defined in [12]. Whether SRVCC and inter-RAT PS handover can be processed in parallel depends on the UE and the target RAT capabilities. Hereafter, the discussion on how SRVCC activation may influence the network performance is provided.

The SRVCC feature aims at improving the quality of voice services by saving voice calls from being dropped due to running out of E-UTRAN coverage. Hence, dropped call statistics and user perceived quality of voice services may be improved after SRVCC activation.

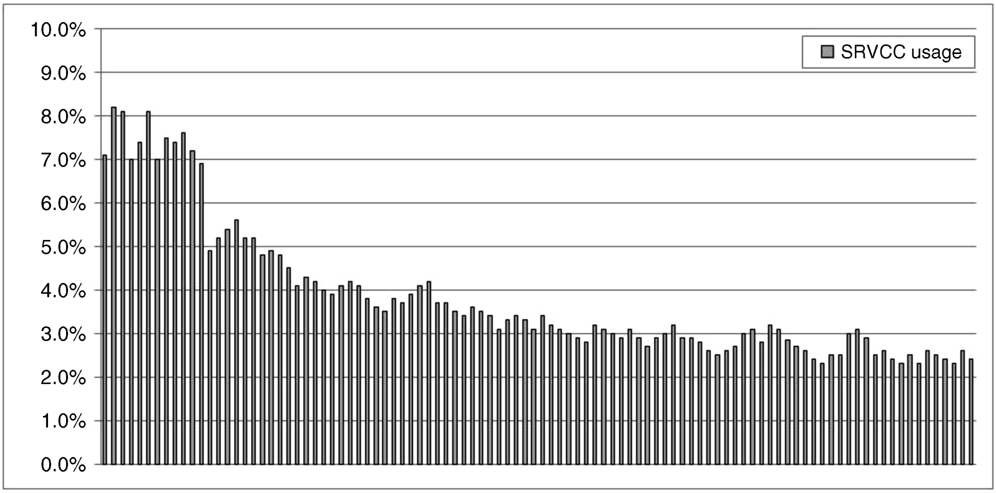

Figure 12.63 Percentage of calls ended with SRVCC over 100 days period.

Although with wider LTE deployment the usage of coverage-driven SRVCC decreases in time, as depicted in Figure 12.63. The percentage of calls ended with SRVCC over 100 days period, the procedure can be still useful, for example, for offloading purposes when LTE becomes saturated with a high number of VoLTE calls.

It should be emphasized that the introduction of SRVCC may, however, entail some compromise of the non-voice services performance. In scenarios where inter-RAT PS handover of non-voice related EPS bearers and SRVCC cannot be executed simultaneously, the latter takes precedence and only the inter-RAT PS-to-CS handover is executed. Consequently, the re-establishment of PS resources in the target cell for continuation of non-voice sessions is deferred which results in longer service interruption times. If the target RAT is UTRAN, SRVCC and inter-RAT PS handover can be executed in parallel only if both the target network and the UE support the PS handover functionality. If the target RAT is GERAN, SRVCC and inter-RAT PS handover can be performed simultaneously only if both the target network and the UE support the DTM Handover. DTM Handover, standardized in 3GPP Release 7 [28], provides GERAN with the means for simultaneous execution of CS domain and PS domain handovers [28]. It efficiently combines standard CS and PS handover procedures so that CS and PS resources are allocated in the target cell before the terminal leaves the source cell. Originally, DTM Handover had been meant for GERAN-to-GERAN and UTRAN-to-GERAN transitions but it can be re-used also in the case of handovers from E-UTRAN. It should be noted here that the pure DTM capability even complemented with the PS Handover but without the DTM Handover is not enough to allow simultaneous SRVCC and inter-RAT PS handover execution towards GERAN cell. It only allows the establishment of the PS connections in parallel to the CS call and to perform the routing area update over the CS signaling channel (using the GTTP protocol) [28].

If the inter-RAT PS handover cannot be processed in parallel to the SRVCC, only CS resources are pre-allocated to the UE and smoothly accessed after switching to the target cell. PS resources for non-voice-related EPS bearers can be established in the new cell after the successful execution of the routing area update (with MME interaction) that in turn may be attempted upon completion of the SRVCC handover [32]. Such a procedure results in the protracted interruption time for non-voice services if such were active upon the triggering of the SRVCC handover. Moreover, if the target RAT is GERAN and DTM is not supported by either the network or the UE, the PS connection set-up must be postponed until the CS call is completed. Consequently, the suspend procedure towards the source MME (as defined in [29]) must be executed. When the CS call is completed, the suspended PS sessions may be resumed via the corresponding procedures described in [29].

Having completed the CS call in UTRAN or GERAN, the UE follows standard idle or PS mode (if any PS session remains active) mobility management procedures. With the appropriate parameterization of those procedures, the UE may be forced to camp back to E-UTRAN as soon as a suitable cell is available.

Up to now, several options of SRVCC have been defined, such as the enhanced SRVCC (eSRVCC) procedure introduced along with 3GPP Release 10 aimed at the reduction of delay, caused by longer path switching, in a roaming scenario. The eSRVCC is targeted for roaming cases as, according to the Release 8 architecture, the anchor point for voice traffic is located in the IMS of a home network, despite the UE being in a visited one. The eSRVCC supporting architecture implies the introduction of two new network entities, located in the serving network, namely, the Access Transfer Gateway Function (ATGW), which is the anchor point for media traffic and the Access Transfer Control Function (ATCF) which controls ATGW. Inclusion of the ATGW improves the delay caused by path switching whenever the SRVCC handover needs to be performed [33,34].

The inter-system interworking mechanisms for voice connections are complemented with so-called Reverse SRVCC (rSRVCC) which incorporate handovers from UTRAN/GERAN CS domain to E-UTRAN for voice calls either previously handed over from E-UTERAN to UTRAN/GERAN CS domain (via SRVCC) or directly set up in UTRAN/GERAN CS domain but anchored in IMS [32,35]. CS to PS SRVCC may not be necessarily triggered due to coverage holes but rather when, regardless of the serving cell conditions, the LTE signal level is strong enough to handle voice connection. Consequently voice users transferred to E-UTRAN can benefit from the better experience offered by LTE.

The applicability of SRVCC is not only limited to voice connections only but can be also used for video calls which are anchored in IMS. The Video SRVCC (vSRVCC) helps to maintain service, which comprises voice and video bearers, when the UE is running out of E-UTRAN coverage by relocation of a video call to 64 kbps bearer for multimedia in UTRAN. It should be noted that when the target RAT is GERAN, only the voice component is transferred using the SRVCC, hence the video call is not sustained but replaced with a voice call [32].

12.8.4 Idle Mode Signaling Reduction

Smooth LTE and legacy systems interworking requires the mobility management features to be complemented with an efficient inter-system location management mechanism. For that purpose Idle Mode Signaling Reduction (ISR) functionality has been standardized by 3GPP [12]. This enhancement requires S3/S4 based inter-system interworking architecture so that the S-GW is the anchor for UE mobility. The ISR mechanism is a kind of evolution of the LTE-specific tracking area list concept to the inter-RAT scenario. With the tracking area list concept, a UE can be registered to multiple TAs and therefore does not need to perform a TA update every time it crosses TA boundary (unless it camps on a cell of a tracking area it is not registered to). With ISR, a UE can be simultaneously registered to multiple tracking areas of

E-UTRAN and the routing area of UTRAN or GERAN. As long as a terminal moves between RATs but within the registered areas, neither RAU nor TAU is performed (with the exceptions of periodic updates). Hence, the signaling load due to inter-RAT transitions may be reduced. This, however, is possible only at the cost of a paging-related signaling increase that in the case of ISR has to be initiated in both SGSN and MME. Without ISR, when an idle mode UE switches between RATs, the routing area update (if the target is GERAN/UTRAN) or the tracking area update (if the target is E-UTRAN) must be executed which in turn entails the deregistration of a UE from the source RAT. In frequent inter-RAT transition scenarios (e.g., LTE islands on top of GERAN/UTRAN), the "ping-pong" effect may generate so much overall additional signaling traffic that its reduction even at the cost of paging load increase is well justifiable.

The ISR functionality does not influence the standard rules of RAU and TAU procedures associated with the UE mobility within given RAT. Routing and tracking area updates must be executed upon moving to area where a UE is not registered or upon expiry of periodic update timers. These are managed independently for 2G/3G and E-UTRAN. It must be, however, noted that as long as a UE switches between routing areas served by the same SGSN, ISR remains active so that when changing to E-UTRAN, TAU is needed only if the current TA is not on the multiple TA list this UE is registered to. Analogously, tracking are updates in E-UTRAN do not deactivate ISR as long as the serving MME is not changed so that RAU is not required if the current RA matches the one a UE is already registered to. If the serving MME or serving SGSN is changed, ISR is deactivated and tracking or routing area updates following inter-RAT transitions cannot be avoided. ISR gets deactivated also as a result of implicit detach performed by the MME or the SGSN.

Idle Mode Signaling Reduction is applicable also to CS Fallback-capable terminals, that is, entering the GSM or WCDMA network as such does not lead to ISR deactivation [27]. Potential paging messages will be routed (from the MSC via the MME to the SGSN) to both registered tracking areas and routing area. However, any location area update or combined RAU/LAU procedure triggered by CSFB-capable mobile leads to ISR deactivation. For further details related to ISR, refer to [12] and [27].

12.9 Multiple Antenna Techniques for Capacity Increase in LTE

Multiple antenna techniques allow capacity increase by improving the spectral efficiency in terms of bits per hertz per cell (bits/Hz/cell). This means that the capacity and the UE throughput can be increased without the need to acquire licenses for additional frequency bands, or without increasing the number of sites. From this perspective, the multiple antenna techniques are an attractive option for the operator facing high site acquisition costs or with a limited spectrum. Investment in the radio hardware and new antennas is still required but this comes at a fraction of the cost needed for site density increase or bandwidth expansion.

The techniques described in the sections that follow are all compliant with the 3GPP Release 8 specification.

12.9.1 Multiple Antennas in DL

Antenna diversity techniques are one of the cornerstone aspects of the radio-related part of the LTE 3GPP standard. In order to take full advantage of the multiple antenna usage, the mobile terminal relies on the reference symbols that identify each of the antenna ports, and is able to signal back the precoding information whose content and format are also affected by the antenna port multiplicity.

Currently the predominately used configuration of the LTE cell is equipped with two transmit antennas which use a 2 × 2 MIMO mode. Assuming the transmit power per antenna is unchanged, upgrading the eNodeB to four transmit antennas results in immediate gain coming from doubling the total transmit power of the cell. Additionally, the 3GPP Release 8 standard defines four transmit antenna scheme to 2-RX antenna capable UEs, the 4 × 2 MIMO mode. Both open loop and closed loop MIMO modes are specified for four transmission antennas. However, link level simulations results prove that while there are no major differences in performance between 2 × 2 open and closed loop MIMO, the performance of closed loop 4 × 2 MIMO is superior to the 4-TX open loop MIMO counterpart. The 4 × 2 MIMO transmission scheme provides capacity gains in both average and cell edge downlink throughput which can be achieved by the legacy subscriber base of 2RX-only capable UEs. Moreover, in terms of the antenna and transmitter hardware, 4 × 2 MIMO is forward compatible with 4 × 4 MIMO schemes, so it can be regarded as the futureproof investment of the operator.

The principle of closed loop MIMO operation requires knowledge of the downlink channel coefficients at the eNB. To obtain that, the UE measures the channel coefficients (the phase and amplitude shift caused by the multipath propagation conditions) between each pair of its own and the eNB antennas. Based on these channel coefficients, the UE is able to select a preferred precoder setting for the eNB transmission, which is selected from a predefined codebook. The selected precoder is signaled to the eNB in an uplink signaling message along with the rank indicator, which tells the eNB how many parallel streams the UE is able to support with a given wireless channel conditions.

Closed loop 4 × 2 MIMO gains over 2 × 2 MIMO come from the codebook extension. In 3GPP standards, only two or four possible precoder settings are available for 2 × 2 MIMO while for 4 × 2 MIMO the codebook contains 16 possible precoder settings. The larger codebook size allows more opportunities to select a precoder that is closer to the optimal one.

4 × 2 MIMO does not increase the peak throughput as the parallel number of the spatially multiplexed streams is still two – the limit is given by the number of the UE receive antennas. However, due to better performance, it will increase both average and cell edge throughput as shown in Table 12.10.

Gains from 4 × 2 MIMO also rely on the proper antenna cabling and antenna type. The most prevalent four port, dual cross-polarized antenna with half-lambda horizontal spacing between the dipoles is recommended for this functionality. The cross-polarized elements provide sufficient decorrelation to support spatial multiplexing of two streams while the high correlation between the closely spaced co-polarized elements introduces a non-negligible beamforming gain which improves the performance of the UEs especially in moderate and poor radio conditions.

Table 12.10 Performance gain of 4 × 2 CL MIMO.

	UE Throughput Gain	
	Fifth percentile (Cell Edge UEs)	Mean of UE Throughput
4 × 2 CL MIMO vs. 2 × 2 CL MIMO	34% Gain	15% Gain

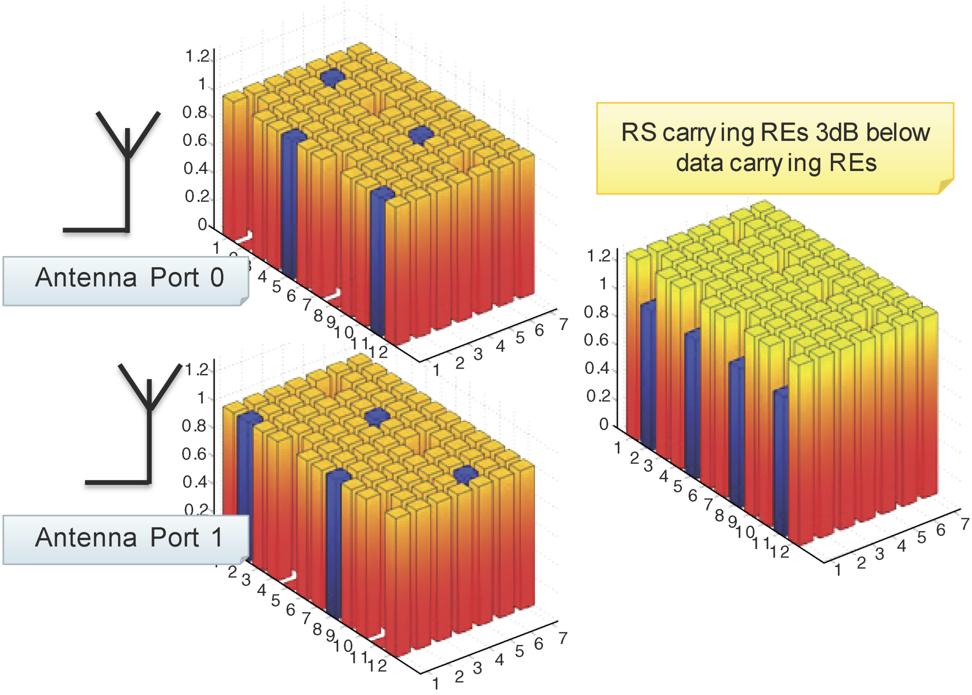

Figure 12.64 Reference signal for 2 TX antennas without the reference symbol boosting.

One important impact that needs to be considered with the upgrade transmit antenna is associated with the cell-specific reference symbols. The reference symbols are used for the coherent demodulation of the DL signal and also for CQI and RSRP calculation by the UE. Cell-specific reference symbols are defined for single two- and four antenna port transmission in the Release 8 standard. Reference symbols are transmitted in the designated resource elements mapped according to Chapter 5, Figure 5.10.

In resource elements which are used for RS transmission, only one antenna port is transmitting whereas other antenna ports are silent, so that the channel can be reliably estimated by the UE. With multiple antennas, this results in lower spectral power density of the reference symbols, as shown in Figure 12.64. In the interference limited scenario, this would lead to the reference symbol SINR degradation which could in some cases render the resulting PDSCH SINR increase useless, since the UEs might not be able to properly demodulate the data carrying symbols anyway, especially on the cell edge. Additionally, as the RSRP calculation is done based on the cell-specific reference symbols of the antenna port 0 and 1, UEs in the cell would experience RSRP decrease in every location, which, for example, would cause the need for the revision of mobility parameters in the network.

In order to address the problem that the reference symbol relative power spectral density may cause, the 3GPP standard allows cell-specific reference signal power boosting [22]. More transmit power for the reference symbols may be allocated, at the expense of the other resource elements in the CRS carrying symbol, improving CRS SINR. The effect of CRS boosting is shown in Figure 12.65.

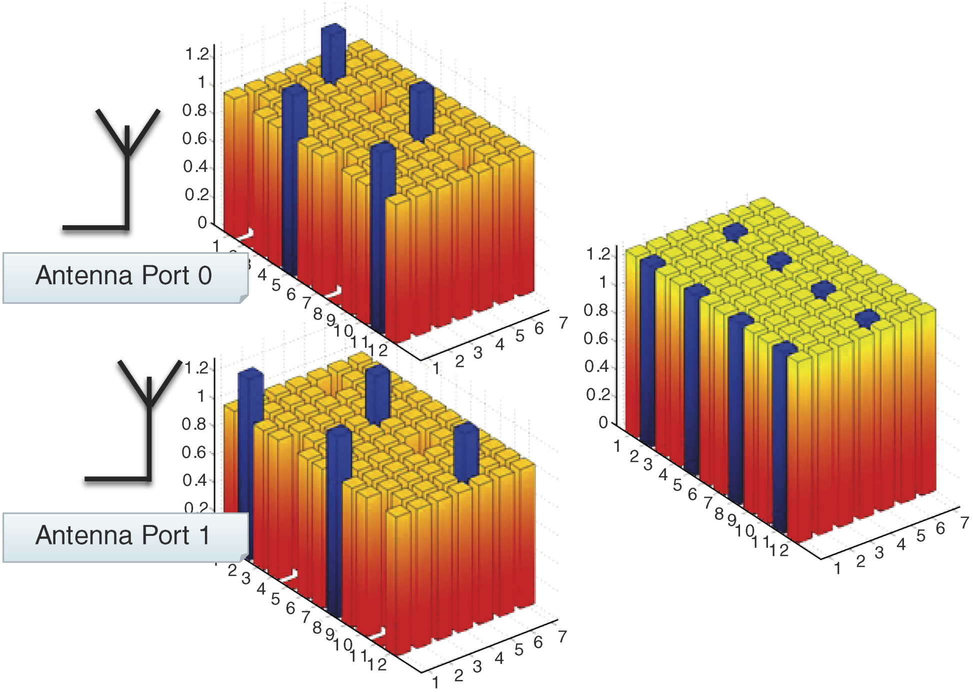

Figure 12.65 Reference signal for 2 TX antennas with reference symbols boosted by 3 dB.

12.9.2 Multiple Antennas in UL

In contrast to downlink, Release 8 and Release 9 did not standardize single user MIMO in UL, so it would seem that from the perspective of multiple stream support, multiple antennas are not required in UL. However, the uplink is usually the limiting direction in LTE and its performance defines the maximum cell range. Multiple antenna techniques in the uplink can be used to match the downlink improvements described in Section 12.9.1, as both the downlink and uplink can use the same set of antennas in the eNB.

Gains from the multiple UL antennas will depend on the following factors:

- Number of the antennas
- Antenna correlation (polarization diversity, antenna element spacing)
- Receiver type
- Wireless channel type
- Level of interference.

12.9.2.1 Power Gain and Diversity Gain

There are two immediate benefits from the increased number of receive antennas. First, is the received signal power gain – more antennas capture more RF energy of the wanted UE, therefore the received signal power will increase with the number of the antenna elements.

The second advantage to be considered is the diversity gain that can be achieved in the wireless channels due to fast fading. In principle, fast fading is caused by the multipath

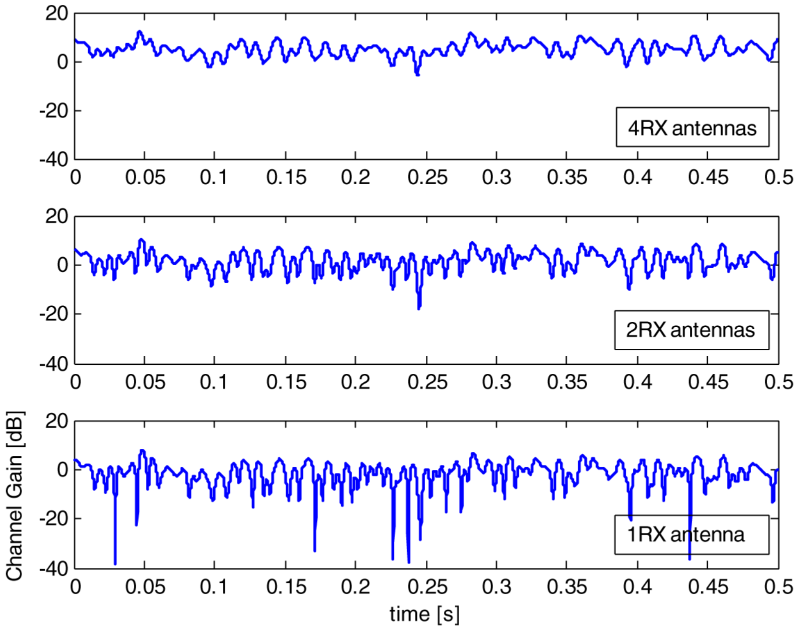

Figure 12.66 Effect of the antenna diversity gain in channels with fading.

propagation of the transmitted signal. In the mobile propagation environment, the multipath components of the radio signal will combine destructively and constructively, resulting in Rician or Rayleigh type of fading pattern. The antenna diversity principle relies on the fact that phase and amplitude relations of the multipath signal components are different on each of the antennas. Consequently, the resulting fading patterns of the same signal are different on each of the antennas. The diversity gain principle is shown in Figure 12.66 – with the increasing number of antennas, the probability of the received signal going to a deep fade is decreased. This phenomenon depends on the channel type, which defines how fast a channel changes, and on the antenna correlation – the lower the correlation between the antennas, the less likely fading pattern will be similar on the antennas in question.

Diversity between the antennas can be improved either by increasing the spacing between the antenna elements, or by using a different polarization of the antenna elements.

Typically the antennas that are used on the sites are vertically stacked cross-polarized dipole panels. The diversity branches are usually constructed from co-polarized elements of the antenna array. The vertical co-polarized elements in the antenna panel are connected by carefully designed phase shifting components in order to achieve the desired vertical antenna pattern. The antenna with more diversity branches houses two or four of such cross-polarized dipole columns in the single panel. To keep the antenna housing reasonably compact, these columns are usually horizontally separated by half of the wavelength of the antenna operating band. In effect, such antennas will usually experience low correlation between the cross-polarized elements while there will be relatively higher correlation between the co-polarized elements of the neighboring dipole columns.

In order to upgrade the cell with more antennas, the operator may either choose to add a second x-pol panel to the already existing one, or to exchange the existing antenna with a dual- or quadruple cross-polarized panel, as described above. While the first option might seem economically reasonable, there are several practical drawbacks to this solution. Adding a second panel to the existing one will put an additional strain on the site mast due to the increased weight and wind load and additionally, space on the site mast could already be scarce since it can be also shared with other operators or other RAN systems.

12.9.2.2 Receiver Type

In the context of the multiple antennas, the role of the receiver is to combine the signals received by the antennas in a way that would aid the signal decoding. Modern software-defined radio receivers are simply algorithms which are processing the received signals converted to digital samples by means of the analog-to-digital conversion.

Software definition of the receiver gives the flexibility of applying different algorithms to different UEs. For example, the interference cancellation algorithms may be used for the reception of the heavily interfered UEs once the interference condition is detected for the particular UE. Various receiver algorithms may also be applied to the distinctive physical channels, such as PUSCH, PUCCH or PRACH, as the performance requirements for these channels are different.

In this chapter, two basic kinds of the receiver algorithms will be explained, with the recommendation regarding deployment of each receiver. These two examples do not complete the potential list of the possible receiver implementations but represent the vast majority of the receiver algorithms deployed currently and in the near future.

12.9.2.2.1 Maximum Ratio Combining (MRC) Receiver

The goal of the Maximum Ratio Combining receiver algorithm is the maximization of the received useful signal power. The wanted signal received on the multiple eNB antennas differs in phase and amplitude due to the propagation, as already explained. In order to combine the signals in a way that would result in the maximization of the wanted signal, a phase adjustment of the receiving antenna branches is needed, so that the incoming signals are always summed in the common phase – a constructive signal addition. This combining principle is called coherent combining, contrary to the incoherent combining case, when the phase of the combined signals is not controlled. Both combining principles are shown in Figure 12.67.

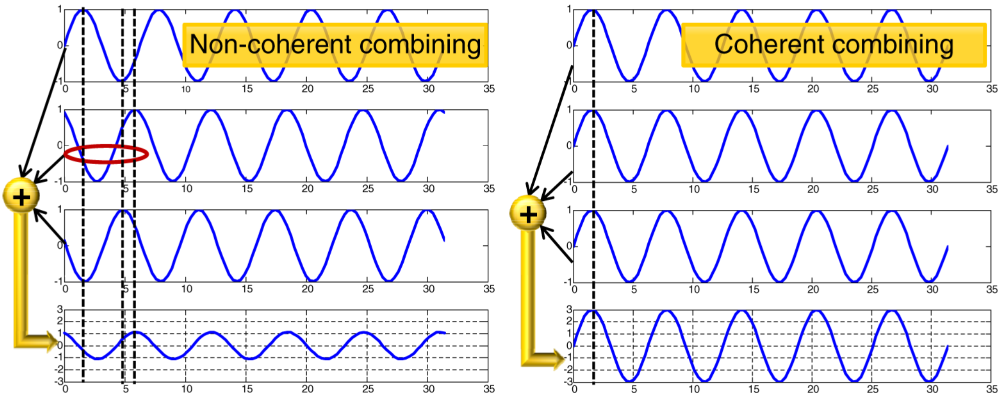

Figure 12.67 Principle of coherent and non-coherent combining types.

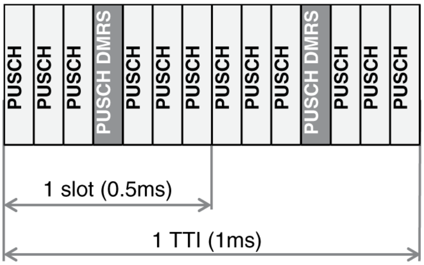

Figure 12.68 PUSCH DMRS sequence in the UL slot.

Apart from the phase adjustment, the MRC algorithm will also compensate for the noise plus interference contribution of the received signal on each of the receiver antenna branches. Consequently the impact of the combining components that carry more noise and interference than the others is mitigated. It may be noted that the variant of this algorithm which omits noise weighting step, called the Equal Gain Combining (EGC), is inferior to MRC by about 1dB for the same target error rate [36].

MRC algorithm definition is given in Equation 12.2.

$$y_{MRC} = \sum_{ant} \frac{y_{ant} h_{ant}^{*}}{\sigma_{ant}^{*}} \tag{12.2}$$

where

y_{MRC}: Received symbol after MRC combining

y_{ant}: Symbol received on one of the antennas

h_{ant}: Complex channel coefficient between the UE transmit and eNB receive antenna

σ_{ant}: noise power received on the antenna.

Complex channel coefficient h_{ant} is the factor by which the transmitted signal is changed in terms of phase and amplitude. The most common and simplest way for the receiver to calculate its value is based on the demodulation reference symbols (DMRS) which are transmitted by the UE. For PUSCH, the DMRS sequence is transmitted over the whole frequency allocation of the UE in the middle of each slot, every 0.5 milliseconds as shown in Figure 12.68. Noise and interference power can be estimated from the received DMRS sequence as well, by subtracting the DMRS from the received signal (see Equation 12.4).

It should be noted that the channel coefficients between the same antennas will also vary in frequency. Since the DMRS sequence occupies the whole band of the UE allocation, channel coefficient can be estimated for every subcarrier.

In order to better explain how the algorithm works, readers can observe that the MRC formula transforms the received signal by applying the complex weights to the antenna elements in the receiver. From antenna theory it is known that it would cause modifications to the antenna receive pattern. A receive pattern of the four omni-directional antennas using MRC algorithm to receive a signal from the UE is shown in Figure 12.69. It can be observed that the receive pattern results in a beam with the maximum gain directed towards the UE, thus maximizing the wanted signal which is the MRC goal.

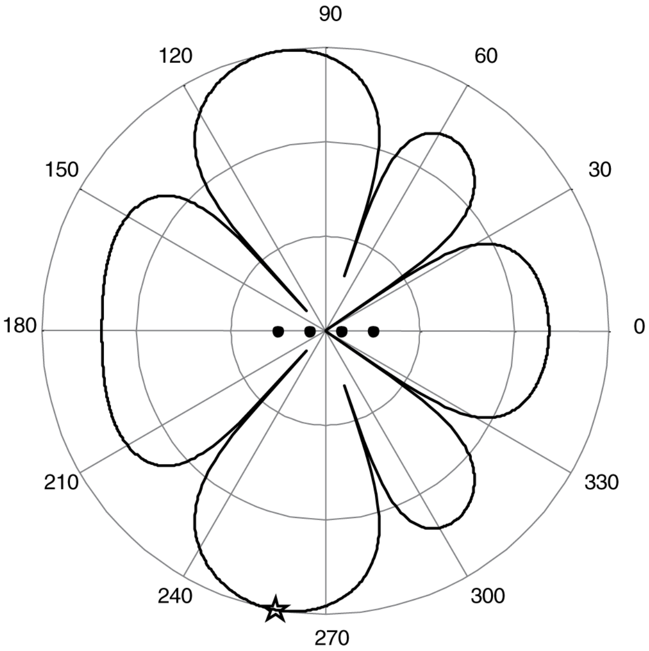

Figure 12.69 MRC algorithm impact on the receive antenna pattern.

By definition, the MRC is not able to distinguish between the thermal noise and the interference. In interference limited networks, where the interference dominates the noise, the performance of the MRC receiver is limited. MRC reaches optimum performance in the noise or coverage limited scenarios.

When upgraded with additional antennas MRC will fully benefit from the received power gain and diversity gain, depending on the number of the antennas, antenna correlation and channel type.

12.9.2.2.2 Interference Rejection Combining (IRC) Receiver

Interference Combining Rejection algorithm goal is maximization of the wanted signal to interference plus noise (SINR) ratio. This is also done by application of the complex weights to the antenna elements. The IRC formula is defined by:

$$y_{IRC} = \frac{h^H R_{dd}^{-1}}{h^H R_{dd}^{-1} h + 1} * y \tag{12.3}$$

where

y_{IRC}: received symbol after IRC combining

$\mathbf{y}$: vector of symbols received on the antennas

$\mathbf{h}^H$: conjugate transpose of the channel coefficient vector

$\mathbf{R}_{dd}$: disturbance (noise+interference) covariance matrix.

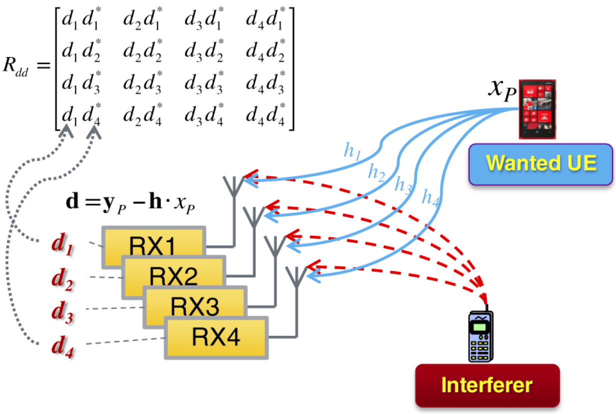
$R_{dd} = \begin{bmatrix} d_1 d_1^* & d_2 d_1^* & d_3 d_1^* & d_4 d_1^* \\ d_1 d_2^* & d_2 d_2^* & d_3 d_2^* & d_4 d_2^* \\ d_1 d_3^* & d_2 d_3^* & d_3 d_3^* & d_4 d_3^* \\ d_1 d_4^* & d_2 d_4^* & d_3 d_4^* & d_4 d_4^* \end{bmatrix}$
$\mathbf{d} = \mathbf{y}_P - \mathbf{h} \cdot x_P$
d_1
d_2
d_3
d_4
RX1
RX2
RX3
RX4
h_1
h_2
h_3
h_4
x_P
Wanted UE
Interferer

Figure 12.70 Spatial disturbance correlation matrix.

The key element of the interference rejection algorithm depends on making use of the spatial properties of the interference. The interference plus noise, or the disturbance signal, is obtained by the eNB per antenna by subtracting the wanted signal in the DMRS symbol phase, where the wanted signal is the known sequence. The disturbance signal can be expressed by the formula:

$$d = y_p - hx_p \tag{12.4}$$

where

d: disturbance signal vector (antenna-wise)

$\mathbf{y_p}$: received DMRS symbol vector

h: vector of wanted UE channel coefficients

$\mathrm{x_p}$: transmitted DMRS symbol.

The interfering signals, just like the wanted signals, will be received by the eNB with different phase and amplitude caused by the multipath propagation and angle of arrival. Contrary to thermal noise, which by definition has zero correlation between the antennas, the interfering signals will exhibit some correlation between any two pairs of the receiving antennas of the eNB. A spatial disturbance correlation matrix is constructed from the disturbance signal received on all of the eNB antennas as shown in Figure 12.70.

It should be noted that as the thermal noise does not exhibit any spatial correlation properties, it can contribute only to the diagonal matrix elements, while the interference will contribute to both the diagonal and off-diagonal elements. It can be also proven that if there are no off-diagonal elements present in the disturbance covariance matrix, the IRC formula given by Equation 12.3 will reduce itself to the MRC formula (Equation 12.2). Therefore, the conclusion can be drawn, that the IRC will not bring any performance gains over MRC in the absence of interference.

Since the IRC, like MRC, works by application of the complex weights to the antenna elements, there will be modification to the antenna receive pattern by analogy of that presented to MRC. The IRC pattern in the presence of the interferers (marked X) is shown in Figure 12.71 with the solid line, while MRC pattern is shown with the dotted line. Nulls that are formed in

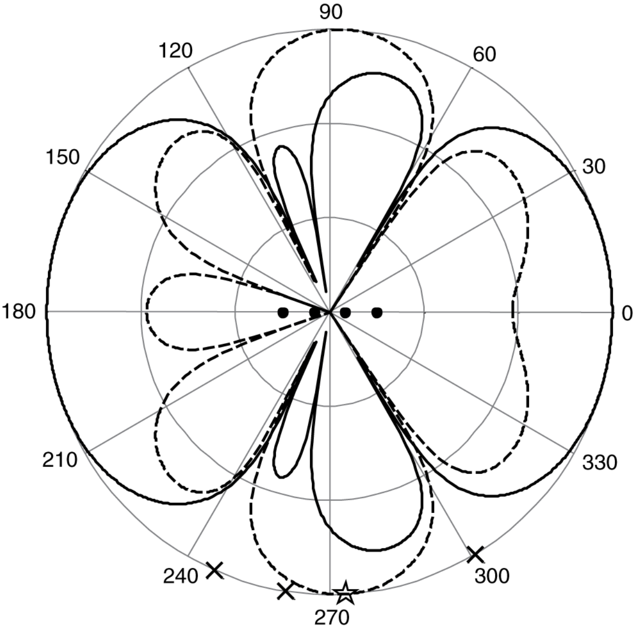

Figure 12.71 Receive pattern modified by IRC algorithm (solid line) and MRC (dotted line) in presence of interferes.

the IRC pattern are directed towards the interferers, which results in attenuation of the interfering signal and maximization of the SINR of the wanted UE (marked as star). On the other hand, the MRC patterns simply ignore the interferers and treat them as noise which does not help with their rejection.

As a rule of thumb, the IRC algorithm is able to cancel N-1 interferers, where N is the number of the antennas that drive the receiver. If the number of the interferers is higher, only the part of the interference will be suppressed.

It is important to note that the IRC algorithm does not make any a priori assumption about the presence or the nature of the interference in the disturbance signal. It will attempt to cancel any disturbance cross-correlation found in the covariance matrix. That might include any residual off-diagonal elements that might be present also in the absence of noise due to numerical error included by the receiver algorithm. For the sake of the interfering signal cancellation, it is required that the interference is present in the DMRS period. That might lead to some consequences in terms of the receiver algorithm performance degradation if the interference correlation changes between the pilot symbols. One of the reasons for these changes can be the variations in the interfering channel coefficients, caused by for example, fast movement of the interfering mobile. The other issue could be faced in the non phase-synchronized networks as shown in Figure 12.72.

In the worst case scenario, the disturbance covariance matrix used for the calculation of the combining weights remains invalid for the duration of half of the slot (250 μs). The issue might potentially affect FDD networks where the network phase synchronization is not required. Link level simulations performed for the worst case synchronization scenario indicate that a 2dB loss compared to a perfect synchronization can be expected in the case of a single interferer.

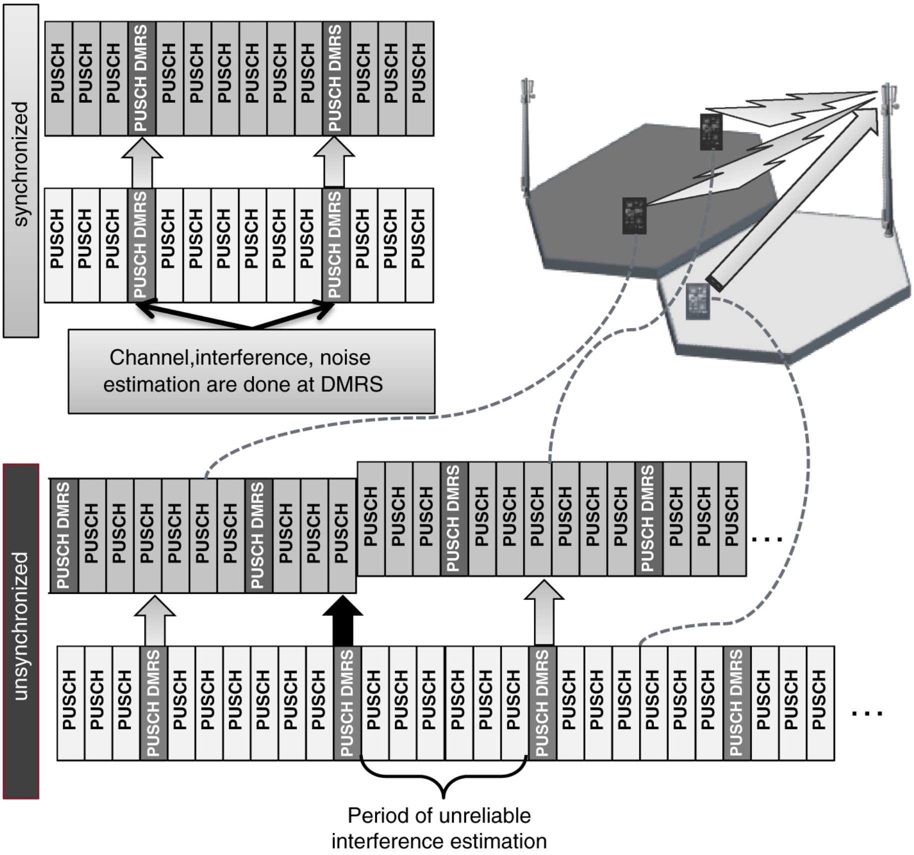
synchronized
PUSCH
PUSCH DMRS
Channel,interference, noise estimation are done at DMRS
unsynchronized
...
Period of unreliable interference estimation

Figure 12.72 Impact of timing misalignment on interference estimation.

Figure 12.73 illustrates the signal plus noise and interference ratio required to reach the 10% BLER target for PUSCH, assuming a fixed MCS level in the EPA30 channel and 4 RX antennas configured for the uplink reception. As expected, there are no differences in the noise-only scenario as no IRC gain can be assumed in this case. IRC interference cancellation capability is most prominent in the single interferer case and it decreases with the increasing number of the interfering sources, however, in each case, the MRC is being outperformed – the SINR requirement of the MRC is the same irrespective of the number of interferers. Performance of IRC depends also on interference over thermal noise ratio (IoT) which is also shown in Figure 12.73 where three different IoT levels ranging from −25 dB to −5 dB were considered. In real networks the IoT levels will mostly be correlated to the inter-site distance, with low IoT levels being experienced mostly in the networks with large distances between the interfering cells. Additionally, since IoT depends on the distance and transmit power of the interferer, it can be expected that it will be higher in the cell edge of the interference limited cell than nearer to its center. This property positions IRC algorithm as a good candidate feature for improving performance of the cell edge UEs in the interference limited networks.

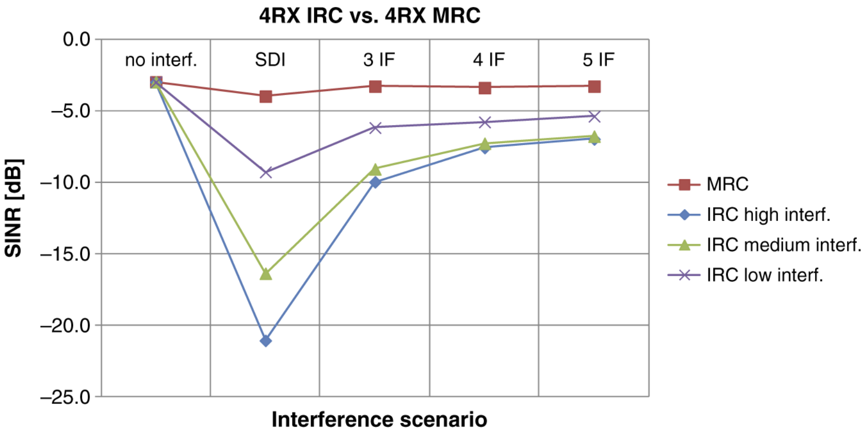

Figure 12.73 Link level performance comparison between MRC and IRC for various IoT levels.

IRC susceptibility to fast channel variations that was already mentioned is pictured in Figure 12.74. The IRC receiver SINR target requirements for PUSCH in ETU70 channel increase compared to EPA30, since the channel variations are more frequent for the ETU70 channel and the noise plus interference covariance matrix estimation becomes less reliable. Since the MRC receiver does not rely on the disturbance covariance matrix accuracy, it is much less sensitive to the channel variations.

12.9.2.3 System Level Performance Gains of Multi-Antenna Uplink Receivers

Gain from multiple antennas depends on the receiver type and on the interference condition in the network. In this section system-level simulation results are presented for the IRC and MRC

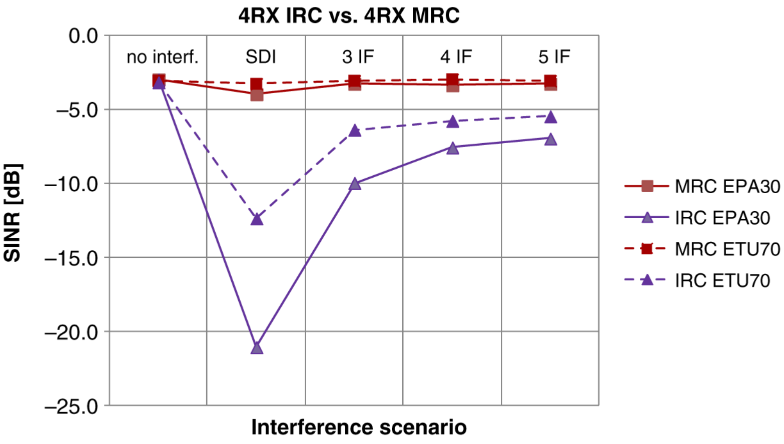

Figure 12.74 Link level performance comparison between MRC and IRC for channels with two different Doppler spreads.

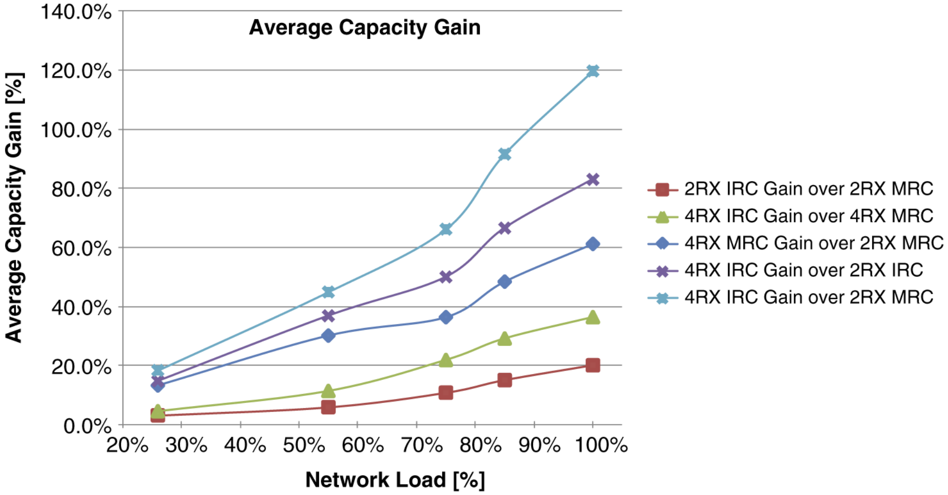

Figure 12.75 Average capacity gain in uplink with different antenna and receiver types.

receivers configured with two and four antennas. The results are summarized in Figure 12.75. The simulation was performed with different network loads which are expressed in terms of the PRB utilization ratio in the cells within the network. The capacity gains are given in terms of the PRB normalized throughput.

It can be observed that upgrading the receiver with more antennas brings an immediate gain in terms of the capacity. It is visible even in the lightly loaded network resulting from the power and diversity gain which improve the uplink SINR.

The IRC algorithm gain strongly depends on the network radio interference level which corresponds to the system load. More receiver antennas configured with the IRC receiver additionally enhance the IRC processing gain according to the N-1 interference cancellation rule of thumb that was described earlier in this section.

Fully loaded network cell edge performance (assumed as the fifth percentile of the UE uplink throughput) is presented in Figure 12.76. The interference over thermal noise ratio is far greater at the cell edge, since the wanted UE is closer to the interfering UEs transmitting in the neighboring cells. As a result IRC capacity gains are higher for the cell edge UEs compared to the average gains.

12.9.2.4 Multiple Antenna in Inter-Cell Joint Uplink Reception

The potential of multiple antennas' combining techniques for the capacity increase can be also extended to the antennas connected to the other cells. This is generally what is behind the concept of uplink Coordinated Multipoint (CoMP) reception. The interference coming from the UE transmitting in the neighboring cell close to the cell edge can be turned into the useful signal if combined jointly with the signal received by the serving cell antennas. The major technical obstacle is caused by the necessity of exchanging a huge amount of raw signal samples between the cells that are involved in the joint combining. Usually a dark fiber is required to provide the required throughput and latencies for such an operation.

An intermediate step which bypasses the abovementioned requirement is the intra site eNB UL CoMP solution, which allows the combining of the UL signals from the co-located cells.

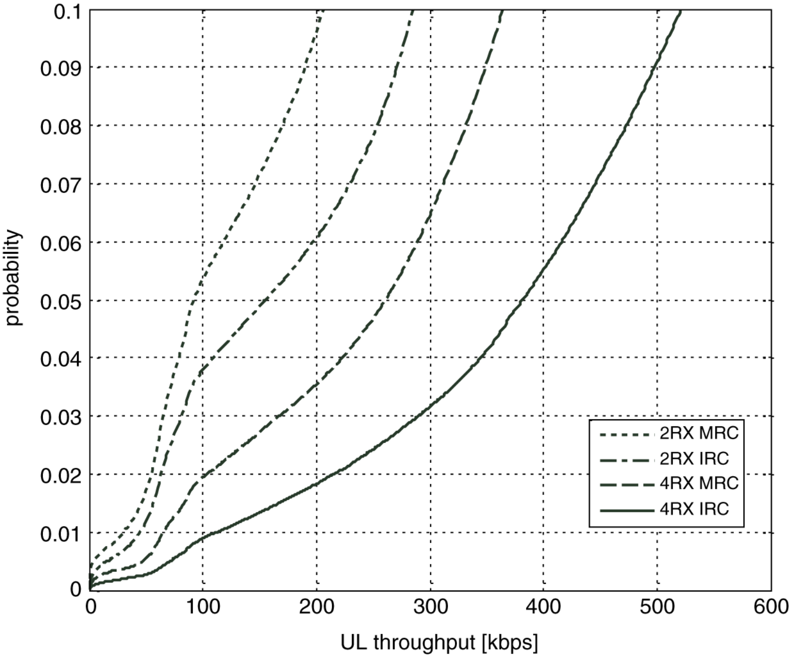

Figure 12.76 Cell edge performance gain in uplink with different antenna and receiver types.

The site solutions that share the baseband processing have no logistic problem associated with the data exchange between the cells, as data from the co-located cells are already processed by the same unit. As another practical advantage, the IRC algorithm can be used to remove the interference of the UEs that are originally transmitting in the neighboring cell used for joint combining. In practice, joint combining will be possible only in the overlap region of the intra eNodeB cells, as shown in Figure 12.77. The reason is that signals received by both cells' antennas need to be balanced to some extent, therefore only a part of the cell area will be subject to the capacity increase. On the other hand, the solution is attractive since it requires no additional hardware expenses to the existing sites.

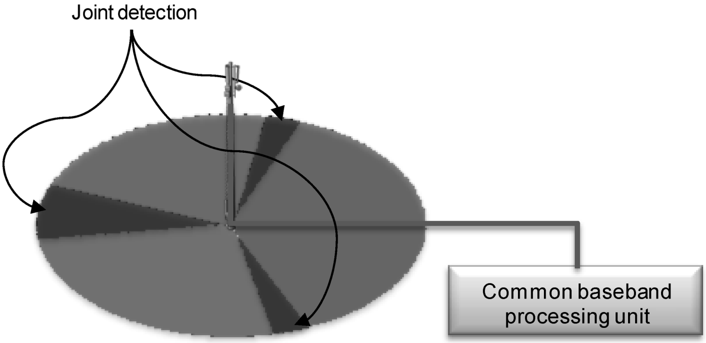

Figure 12.77 Intra eNB uplink CoMP.

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