VŠB – Technická univerzita Ostrava
Fakulta elektrotechniky a informatiky
Katedra telekomunikační techniky

Vývoj standardů mobilních sítí

Evolution of Mobile Network Standards

2013 Martin Talaš

VŠB - Technical University of Ostrava
Faculty of Electrical Engineering and Computer Science
Department of Telecommunications

Bachelor Thesis Assignment

Student: **Martin Talaš**

Study Programme: B2647 Information and Communication Technology

Study Branch: 2601R013 Telecommunication Technology

Title: Vývoj standardů mobilních sítí
Evolution of Mobile Network Standards

Description:

1. Describe the development of standards of mobile networks (Release 99 - Release 12).
2. Describe in detail the differences between physical layer of UMTS (Release 7) and LTE/SAE (Release 10).
3. Map the current state of deployment of LTE/SAE technology in the world.
4. Analyze the possibility of deploying and development the LTE/SAE in the Czech Republic in terms of legislation, capacity demands on the backbone network and frequency planning.

References:

The Mobile Broadband Standards [online]. France, 2011 [cit. 2011-10-24]. Available from WWW: <http://www.3gpp.org>
YI, SeungJune. Radio protocols for LTE and LTE-advanced. Hoboken: John Wiley, 2012, p. cm. ISBN 978 -111-8188-538.

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

Supervisor: **Ing. Libor Michalek, Ph.D.**

Date of issue: 16.11.2012

Date of submission: 07.05.2013

prof. RNDr. Vladimír Vašinek, CSc.
Head of Department

prof. RNDr. Václav Snášel, CSc.
Dean of Faculty

Prohlášení studenta

Prohlašuji, že jsem tuto bakalářskou práci vypracoval samostatně. Uvedl jsem všechny literární prameny a publikace, ze kterých jsem čerpal.

V Ostravě dne: 18.července 2013

....
podpis studenta

Poděkování

I would like to thank everyone who supported me with this thesis especially to Ing. Libor Michálek, Ph.D. for his professional help and comments.

Abstrakt

Tato bakalářská práce pojednává především o vývoji LTE technologií a jejich možnostech nasazení v České Republice a ve světě. Práce se nejprve zaměřuje na vývoj mobilních standardů od nástupu sítí třetí generace, Release 99, až po doposud nejnovější Release 12, kde jsou postupně probrány vrcholové telekomunikační technologie a jejich přednosti. V práci jsou dále popsány rozdíly fyzických vrstev mezi technologiemi HSPA+ a LTE, jelikož se jedná o další evoluční krok v oblasti datových přenosů. Popis obsahuje blokové srovnání od samotné inicializace transportního kanálu, po přenosovou cestu a opětovného získání užitečné informace. Vývoj LTE sítí ve světě pojednává o aktuálním stavu vývoje a rozšíření této technologie. Podrobně jsou zde popsány země, kde se LTE používá spolu se srovnáním použitých frekvenčních pásem. Poslední část řeší otázku vývoje a nasazení LTE v České Republice. S ohledem na aktuální stav sítí jednotlivých operátoru je sekce zaměřena také na legislativu, páteřní sítě a frekvenční plánování, s čímž souvisí také očekáváná aukce z digitální dividendy.

Klíčová slova

Mobilní sítě, HSPA, LTE, vývoj standardů, evoluce mobilních sítí

Abstract

This bachelor thesis deals primarily with a development of LTE technologies and its possibilities of deployment in the Czech Republic and abroad. The thesis is initially focused on the development of mobile network standards since the advent of 3rd generation networks in Release 99 up to the newest Release 12 where the main telecommunication technologies are continuously described along with their advantages. As the LTE represents next evolution step in a field of mobile data transmission, the comparison of LTE and HSPA+ physical layers is also included. Among other it describes information blocks from transport channel over the transmission path and regaining of user data. The development of LTE networks in the world deals with an actual progress of the deployment of this technology. In detail, there are described countries where the LTE is in a commercial service among with a comparison of used frequency bands. Addressing with issue of development and deployment of LTE in the Czech Republic is a content of the last part. With regard to the current network state of each provider, it is also focused on legislation, backbone networks and frequency planning which is closely related to the forthcoming auction of the Digital Dividend.

Key words

Mobile networks, HSPA, LTE, standard development, evolution of mobile networks

List of Acronyms

Acronym	Anglický význam
3GPP	3rd Generation Partnership Project
AICH	Acquisition Indicator Channel
ALG	Application Level Gateway
AN	Access Network
ANR	Automatic Neighbour Relations
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BEM	Block Edge Mask
BF	Beam Forming
BSC	Base Station Controller
CA	Carrier Aggregation
CCTrCH	Coded Composite Transport Channel
CDMA	Code Division Multiple Access
CN	Core Network
CoMP	Coordinated Multipoint
COPS	Common Open Policy Service
C-RNTI	Cell Radio Network Temporary Identifier
CRC	Cyclic Redundancy Check
CS	Circuit Switching
CSCF	Call State Control Function
CSFB	CS Fall Back
CSI	Channel State Information
ČTÚ	Czech Telecommunications Office (Český Telekomunikační Úřad)
D2D	Device to device
DC-HSDPA	Dual Carrier HSDPA
DCI	Downlink Control Information
DL-SCH	Downlink Shared Channel
DRX	Discontinuous Reception
DTX	Discontinuous Transmission

DWDM	Dense Wavelength Division Multiplexing
DwPTS	Downlink Pilot Timeslot
E-DCH	Enhanced Dedicated Channel (Transport uplink channel used in 3G)
EDGE	Enhanced Data rates for GSM Evolution
E-HICH	E-DCH HARQ Indicator Channel
EIRP	Equivalent Istropically Radiated Power
eMBMS	Evolved MBMS
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-RGCH	E-DCH Relative Grant Channel
ETSI SMG	European Telecommunications Standards Institute - Special Mobile Group
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EVDO	Evolution Data Optimized
FDD	Frequency Division Duplex
GAN	Generic Access Network
GERAN	GSM/EDGE Radio Access Network
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GP	Guard Period
GPRS	General Packet Radio Service
GSA	The Global mobile Suppliers Association
GSM	Global System for Mobile Communication
GSMA	GSM Association
HARQ	Hybrid Automatic Repeat Request
HeNB	Home eNodeB
HS-DPCCH	High Speed Dedicated Physical Control Channel
HS-DSCH	High Speed Downlink Shared Channel
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	High Speed Packet Access Plus (Evolved HSPA)
HSUPA	High Speed Uplink Packet Access
IETF	Internet Engineering Task Force
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications

IP	Internet Protocol
IP-CAN	IP Connectivity Access Network
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
I-WLAN	Interworking – WLAN
LTE	Long Term Evolution
MAC	Medium Access Control
MBMS	Multimedia Broadcast Multicast Service
MBSFN	Multimedia Broadcast Single Frequency Network
MCH	Multicast Channel
MCS	Modulation and Code Scheme
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MLB	Mobility Load Balancing
MME	Mobile Management Entity
MNO	Mobile Network Operator
MRO	Mobility Robustness Optimization
MSC	Mobile Services Switching centre
NAT	Network Address Translator
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	OFDM Access
OMA	Open Mobile Alliance
OVSF	Orthogonal Variable Spreading Factor
PBCH	Physical Broadcast Channel
PCC	Policy and Charging Control
PCCH	Paging Control Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
P-CPICH	Primary Common Pilot Channel
PCRF	Policy and Charging Rules Function
P-CSCF	Proxy CSCF
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel

PDU	Protocol Data Unit
PhCH	Physical Channel
PHICH	Physical Hybrid-ARQ Indicator Channel
PMCH	Physical Multicast Channel
PMI	Pre-coding Matrix Indicator
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PS	Packed Switching
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Services
RACH	Random Access Channel
RAN	Radio Access Network
RLC	Radio Link Protocol
RN	Relay Node
RRH	Remote Radio Head
SAE	System Architecture Evolution
SBLC	Service-based Local Policy
S-CPICH	Secondary Common Pilot Channel
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SON	Self Organizing Networks
SRS	Sounding Reference Signal
STUN	Session Traversal Utilities for NAT
SU-MIMO	Single User MIMO
TA	Timing Advance
TBS	Transport Block Size
TrCH	Transport Channel
TTI	Transmission Time Interval
UCI	Uplink Control Information
UE	User Equipment
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink Pilot Timeslot

UTRAN	UMTS Terrestrial Radio Access Network
VAM	Virtual Antenna Matrix
VoLTE	Voice over LTE
W-CDMA	Wideband Code Division Multiple Access
WCIS+	World Cellular Information Service
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

List of Terms

Termín	Význam termínu
2G	It is the second generation of mobile networks so known as GSM.
3G	The third generation of mobile networks introduced in 2000. The technical name Is a UMTS.
4G	The fourth generation of mobile networks also known as LTE networks.
16-QAM	16-point Quadrature Amplitude Modulation
A/Gb interface	The interface provides connection between BSC and MSC/SGSN.
Beam Forming	The transmission or reception signal by combining elements in phased array.
CDMA2000	It is a family of 3G mobile technology standards, which use CDMA channel access to send voice, data, and signalling data between mobile phones and cell sites.
CS Fall-back	It is an LTE functionality used to transform voice call to circuit-switched domain.
Digital Dividend	Rest of the frequency spectrum after swap from analogue to digital transmission (DVB-T in Czech Republic)
E-MBMS	Version of MBMS designed for LTE networks.
E-UTRAN	Version of UTRAN part designed for LTE networks.
eNodeB	Base station of LTE network.
EVDO rev. A	Part of CDMA2000 family. It provides speeds up to 1,4Mbps downlink (bursts to 3.1Mbps) and 800kbps uplink (bursts to 1.8Mbps).
Femtocell	It is a small, low-power cellular base station, typically designed for use in a home or small business.
NodeB	Base station of UMTS and its successors.
PRB	A Physical Resource Block is the smallest unit of bandwidth assigned by the base station scheduler.
Ping-Pong effect	Situation when the UE is situated on a boundary of two base stations which causes continual switching (hand-over) between them.
S1 interface	It is the interface between RAN and CN in LTE/SAE
X2 interface	It is the interface connecting a neighbour eNodeBs.

Contents

1 Preface

The telecommunication networks are one of the most progressive networks nowadays. It began with transfer of voice and SMS (Short Message Service), through MMS and video streaming to high bit rate Internet access and its services. Increasing number of mobile devices and higher quality of provided services put higher demands on the transmission peak data rate and capacity of networks.

The first part of bachelor thesis is focused on history and present development of mobile networks since year 2000. That time was the remaining GSM work transferred to 3GPP and ETSI SMG was closed. Publishing of Release 99 started new age of mobile networks, publicly known as 3G. By the technology optimization and improvement could be in 2004 introduced system HSPA containing HSUPA and HSDPA which allows higher downlink and uplink transmission data peak rate. Release 7 brought an innovated technology HSPA+. This technology is based on the same principles and it is known as 3.5G. The completely new network LTE came with the advent of Release 8. It includes new structure based core network EPC along with high data peak transmission interface. As the most innovated technology is a successor of LTE called LTE-Advanced which also belongs to this evolution.

Comparison of HSPA+ (Rel.7) and LTE (Rel.10) physical layers is a topic of chapter 3. In the chapter is compared each block of physical layer both transmission technologies. The comparison includes channel mapping, coding and rate matching, modulation parameters and spreading principles of HSPA+ and LTE-Advanced. Comparison of transport and physical channels is also included.

Chapter 4 deals with actual deployment of LTE/SAE in the world. For better orientation, it has been split into four areas: Americas includes North and Latin America, Asia Pacific and Oceania describes Asian countries together with Australia and New Zealand, Europe deals with European Union and neighbouring countries, and Middle East and Africa which is mainly about Arabic countries and African continent. Actual situation of deployment is shortly commented in every subsection along with a graph of used frequency bands. Preview and forecast for future development are also part of this chapter.

The aim of the last chapter is an analysis of LTE/SAE deployment in the Czech Republic. Firstly, there is an introduction of all Czech mobile network operators and its current state of the development. Second subsection is mainly focused on frequency bands subjected in forthcoming auction of digital dividend, which are allocated for future LTE networks. Last subsections contain legislation terms necessary to comply with in LTE network deployments and backbone network demands beside to topology efficiency.

2 Mobile Network Standards Evolution

After transfer of the remaining GSM work to 3GPP in summer 2000, ETSI SMG has been closed and new release (Rel.99) was published. It brought the evolution in GSM, relevant to UMTS and working on packet-switched (PS) networks.

GSM networks used circuit-switch telephony initially, with packet-switching added with GPRS. In the UMTS architecture, this dual-domain concept was kept on the core network side. Some network elements were evolved but the concept remained very similar.

When considering the evolution of the 3G system, towards LTE, the 3GPP community decided to use IP (Internet Protocol) as the key protocol to transport all services. It was therefore agreed that the Evolved Packet Core (EPC) would not have a circuit-switched domain but that the EPC should be an evolution of the packet-switched architecture used in GPRS/UMTS. [1]

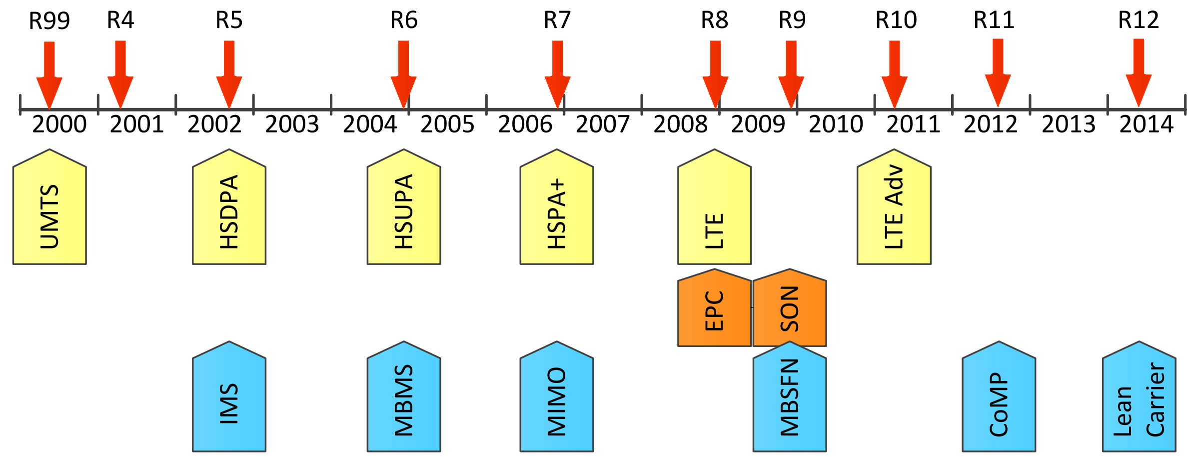

Figure 2.1: *Evolution of Mobile Data Standards*

2.1 Basic Model of GSM and UMTS (Rel. 99) [1]

In March of 2000 there has been released an innovated model of mobile network based on the combination of GSM and UMTS. UMTS refers to the interconnection of a new type of Access Network (AN), the UTRAN to the adapted pre-Release 99 GSM/GPRS Core Network (CN) infrastructure.

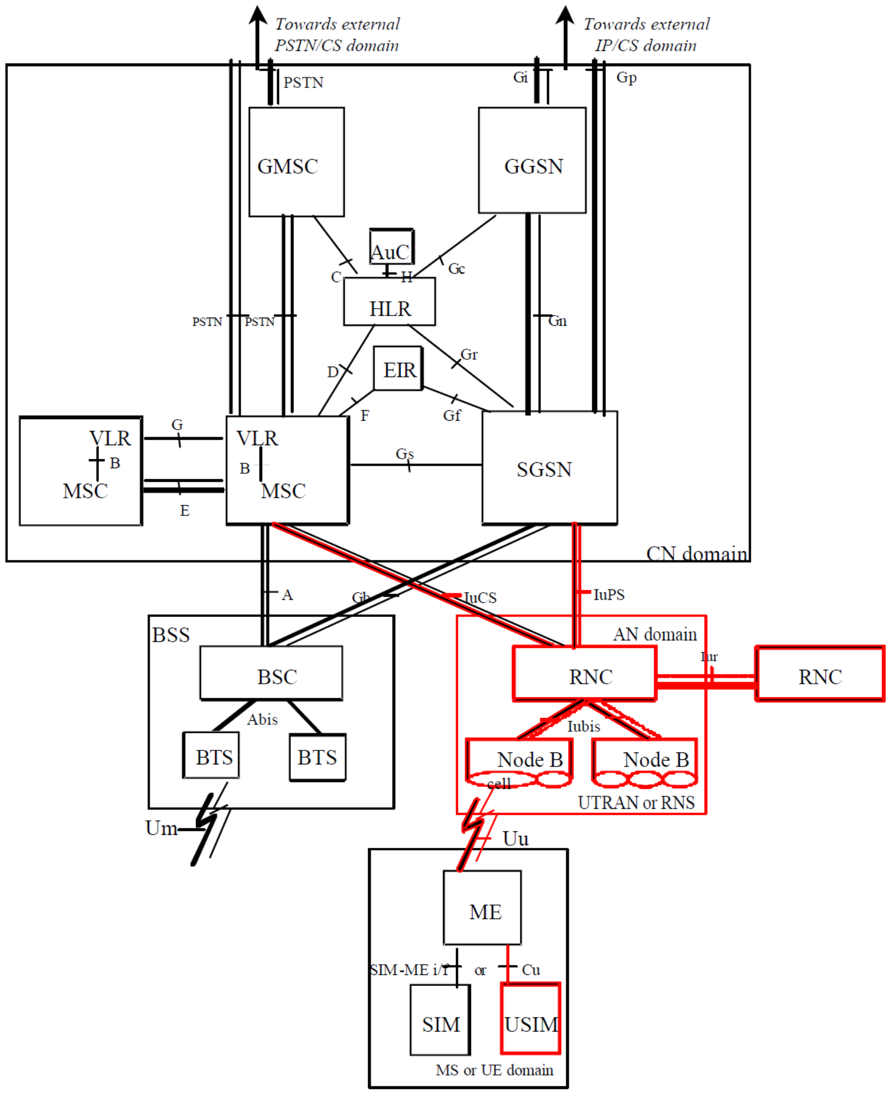

Figure 2.2: *Implementation of UTRAN [1]*

Legend:

- Bold lines: interfaces supporting application traffic (also called "user data");
- Dashed/thin lines: interfaces supporting signalling.
- Red lines and boxes: interfaces and entities specific to UMTS

A basic requirement for Release 99 UMTS was to minimize the impacts on the Core Network when introducing the UTRAN. This principle was achieved to a great extent. The biggest impacts are the creation of a new type of interface between core and access networks, and the "upgrading" of the CN signalling to take into account the new capabilities offered by the UTRAN.

While looking into data rates, the first phase of GPRS (Releases 97 and 98) allowed a maximum of 171,2 kbps. That was achievable by using all eight available timeslots, and in the best radio traffic conditions. The radio interface used for UTRAN, a Wideband Code Division Multiple Access (WCDMA), was originally designed to allow for the Release'99 a maximum (theoretical) peak rate of around 2Mbps.

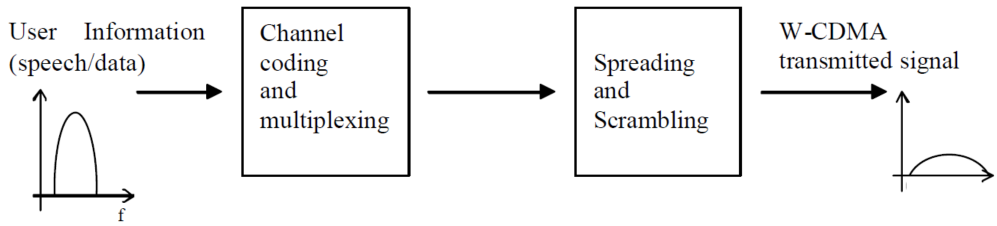

Figure 2.3: *Information to W-CDMA transfer process [1]*

For this, a Direct-Sequence Code Division Multiple Access scheme was chosen. The figure above shows the process applied to the user information.

2.2 Release 4 [2]

Rel-4 was released in 2001 and it contained mostly minor updates. The most important enhancements are the division of the (G)MSC into a transport node, the Media Gateway and a control node, the (G)MSC Server. Furthermore, the standard made the CS Domain bearer-independent: it can be circuit-switched natively, ATM-based or even IP-based. Release 4 conformant equipment has also been deployed.

2.3 Release 5 [2]

2.3.1 IMS

A dedicated subsystem of core network for service support, the IP Multimedia Subsystem (IMS), is an architectural framework for delivering IP multimedia services. Although the PS Domain is an IP Network, it is not designed according the Computer Networks approach.

2.3.2 HSDPA

High Speed Downlink Packet Access (HSDPA) is the first instalment of HSPA. It was added closer to radio interface, in NodeB, for faster channel allocation, better adaptation to varying channel quality and delay reduction. HSDPA enhances the UMTS air interface on the basis of 16-QAM and Hybrid ARQ (HARQ) on physical layer to introduce a downlink shared channel with packet rates up to theoretical value of 14,4 Mbps. A UMTS network with HSDPA is already qualified as "3.5G".

Configurations:

Table 2.1: *HSDPA Rel.-5 configurations*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
16-QAM	1	-	14,4

2.4 Release 6 [2]

Rel-6 was published in 2005 and it is also a major release featuring, among others HSUPA which make together with HSDPA (Rel-5) so-called HSPA network.

2.4.1 IMS supporting services

3GPP standardized only a small number of supporting services, e.g. Push Service, Instant Message Service and Presence Service.

2.4.2 GAN

The goal of GAN is to attach a generic IP-based Access Network to the 3GPP Core Network via the A/Gb interface. This is achieved by using an additional network element, masking the GAN to the Core Network. A number of 3GPP-specific protocols is employed to this end. Functionally and architecturally, a GAN is equivalent to a GERAN.

2.4.3 Update of the charging architecture

A harmonized charging architecture was introduced for bearer, subsystem and service level. Pre-Release 6, for each level and each domain there had been developed an independent charging architecture.

2.4.4 Flow-based Charging

Until the advent of Flow-based Charging, charging is only possible with the resolution of a bearer: when two or more service-level flows utilize the same bearer, they cannot be differentiated. Flow based Charging supports a service-specific charging on the bearer-level of any resolution and, furthermore, allows for the coordination of charging on the bearer subsystem and service levels.

2.4.5 HSUPA

High Speed Uplink Packet Access (HSUPA) extends the downlink HSPA from Rel-5 by adding a dedicated uplink channel with bandwidth up to 5.76Mbps achieved, among others, by QPSK modulation - since uplink a sufficient number of codes has been available, there is no need to introduce shared channels. HSUPA in Rel-6 is specified only for FDD and uses soft handover, same as Rel-99.

Configurations:

Table 2.2: *HSUPA Rel.-6 configurations*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
QPSK	1	-	5,76

2.4.6 MBMS

In scenarios such as multicast of sport events, multi-party conferencing or broadcast of emergency information it may happen that several UEs in a cell receive the same data stream. The Multimedia Broadcast Multicast Service (MBMS) enables a resource efficient data transfer to many

UEs in parallel: by means of an additional network element in the Core Network and new protocols, the data is sent only once to each cell and all UEs access the same channel for receiving it.

2.5 Release 7 [2]

2.5.1 PCC

Whereas in previous releases, the authorization of QoS in the PS Domain by the IMS (via SBLC) and Flow-based Charging relies on an independent mechanism, Policy and Charging Control (PCC) provides a single policy infrastructure in order to handle both kinds of policies. Furthermore, PCC is applicable to any IP-CAN, and to any service network. Together with the introduction of PCC, the COPS protocol between GGSN and PCF/PCRF was abandoned and replaced by Diameter.

2.5.2 HSPA+

This is an enhancement of the HSPA technology, which has been developed to exploit 5MHz bandwidth as much as possible. For downlink, it uses 64-QAM with maximum peak rate of 21Mbps or combination of 16-QAM and 2x2 MIMO with data rate up to 28Mbps. The uplink side is enhanced by modulation 16-QAM, which doubles the uplink up to 11,5Mbps.

Configurations:

Table 2.3: *HSPA+ Rel.-7 downlink and uplink configurations*

	Modulation	Used Carriers	MIMO	Data Rate (Mbps)
DL	16-QAM	1	2x2	28
	64-QAM	1	-	21
UL	16-QAM	1	-	11,5

2.5.3 HSUPA for TDD

The specification of HSUPA has been extended to also work with TDD.

2.5.4 Continuous Packet Connectivity [10]

3GPP Release 6 mobile terminal keeps transmitting the physical control channel even if there is no data channel transmission. Release 7 mobile terminal cuts off the control channel transmission when there is no data channel transmission, allowing it to shut down the transmitter completely. This solution is called discontinuous uplink transmission and it brings clear savings in transmitter power consumption.

A similar concept also is introduced in the downlink where the terminal must wake up only occasionally to check if the downlink data transmission is starting again. The terminal can use the power-saving mode during other parts of the frame if there was no data to be received. This solution is called downlink discontinuous reception. The discontinuous transmission concept is illustrated in Figure 2.4 for Web browsing.

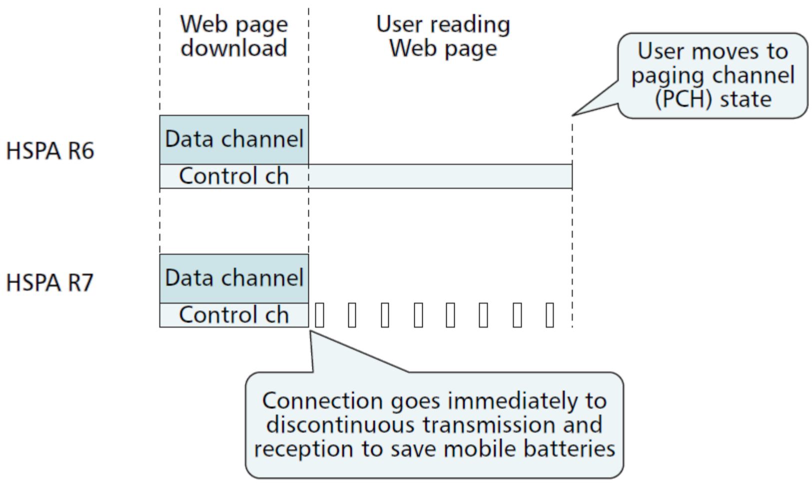

Figure 2.4: *Discontinuous transmission and reception with CPC [10]*

2.5.5 Enhanced CELL_FACH state [11]

Although CPC helps to keep HSPA users in the CELL_DCH state, eventually users who have not had data to send for a period of time will be moved to the CELL_FACH state. Users can send data over the FACH channel but the data rate is very limited. Thus, if the user has a significant amount of data to send, it is preferred to move the user back to CELL_DCH state so they can send the data over the HS-DSCH channel (i.e. the HSDPA traffic channel) to experience improved throughput rates. However, moving users back to the CELL_DCH state requires signalling over the limited data rate FACH channel and thus can take some time. In order to reduce the latency associated with moving from CELL_FACH to CELL-DCH state, Rel-7 defined an enhanced CELL_FACH state that allows the users to transmit on the HS-DSCH channel while in CELL_FACH state. This enables the user to send the signalling required to move from CELL_FACH to CELL_DCH over the much faster HS-DSCH channel, greatly reducing setup times and improves user experience.

2.5.6 IMS support of UEs behind NATs

The original 3GPP idea is that of the UE as a single piece of equipment connected directly to the RAN. It is also possible to install a Network Address Translator (NAT) and a firewall between the UE and the UMTS Network. 3GPP specifies two solutions for this problem. One solution is employing an Application Level Gateway (ALG), co-located with the P-CSCF. The ALG performs deep packet inspection and has application-specific knowledge that allows it to translate appropriately, e.g. IP addresses in session descriptions, possibly in interaction with the NAT. Alternatively, the Session Traversal Utilities for NAT (STUN) is employed. The STUN specification includes a STUN Server in the external network—the IMS in our case—which the entity behind a NAT—the UE in our case—can query in order to learn its external address. This allows the UE to include right away the correct address in its session description. Of course, the UE must be aware that it is supposed to contact the STUN Server.

2.5.7 MIMO

Multiple Input, Multiple Output (MIMO) is a technique of streaming signal by more antennas in the same time. Because MIMO transmits via the same channel, transmission using cross components not equal to 0 will mutually influence one another. Version of 2x2 MIMO used in Release 7 is shown in Figure 2.5.

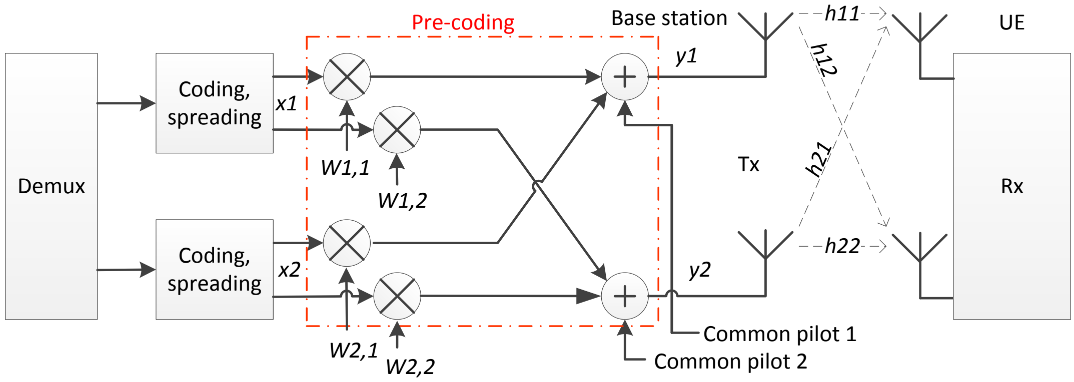

Figure 2.5: *Version of a 2x2 MIMO system*

The signal is split onto two separately coded streams. Before each of the virtual-antenna signals are fed to the physical antennas, linear pre-coding is used. For each of the streams, the pre-coder is simply a pair of weights. Stream x_1 is multiplied with the complex weight $w_{1,1}$ and $w_{1,2}$ before being fed to physical antenna.

2.6 Release 8 [3,4,5]

3GPP Rel-8 published in 2008, provided significant new capabilities, through not only enhancements to the W-CDMA technology, but with the addition of OFDM technology through the introduction of LTE as well.

2.6.1 Dual Carrier HSDPA

Release 8 combines 2x2 MIMO and 64-QAM which allow transmitting six bits per symbol, instead of four bits (16-QAM in Rel-7) allows to get theoretical downlink peak rate up to 42 Mbps. Adding the capability to perform dual carrier operation for HSPA+ (transfer by two adjacent 5 MHz bands covering same area) has been achieved this peak rate even without using MIMO technology.

Configurations:

Table 2.4: *HSPA+ Rel.-8 downlink configurations*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
64-QAM	1	2x2	42
	2	-	

2.6.2 LTE

The release 8 brings also Long Term Evolution (LTE) defines a physical layer describing an OFDM access for downlink and SC-FDMA for uplink which work with bandwidths from 1.4MHz up to 20MHz. As a carrier option, the LTE supports FDD and TDD as well as E-MBMS broadcast capabilities. User data rate has been increased up to 325 Mbps for downlink and 75,4 Mbps for uplink in 20 MHz bandwidth. The LTE uses adaptive modulation QPSK, 16-QAM or 64-QAM depends to actual transmission conditions. A part of the functionality is application of MIMO 2x2 or 4x4.

2.6.3 SAE

System Architecture Evolution (SAE) is a new simplified architecture of network, structured as an all-IP network. It brings higher throughput, lower latency RANs and support of 3GPP legacy systems (GPRS, UMTS, etc.) as well as non-3GPP systems (WiMAX or CDMA2000). The main component of SAE is the Evolved Packed Core (EPC).

2.6.4 EPS

Release 8 also introduced Evolved Packet System (EPS) consisting of a new core network called the Evolved Packet Core (EPC) coupled with a new air interface based on OFDM called Long Term Evolution. It is the most basic form, where the user plan consists only base station and a core network (GW). The node Mobile Management Entity (MME), performs control planning, is separated from the node that performs bearer planning. It was designed to not only for evolution from 3G architecture, but also to provide support for non 3GPP technologies as WiFi etc. The EPS bring a wider range of QoS capabilities, improved PCC, and advanced authentication mechanisms. The basic EPS architecture is illustrated in Picture 2.6.

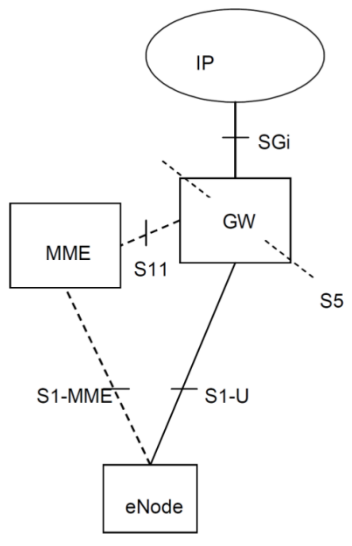

Figure 2.6: *Basic EPS architecture [3]*

2.6.5 Evolved MBMS

Evolved MBMS (eMBMS) allows streaming of multicast/broadcast data, such DVB-H, through LTE network.

2.7 Release 9 [4,5]

2.7.1 DC-HSDPA & MIMO

The dual-carrier HSDPA coupled with 2x2 MIMO described in Release 9, allows to get to theoretical downlink peak rate 84 Mbps on UEs. New specifications also bring 2x10 MHz bandwidth.

Configuration:

Table 2.5: *HSPA+ Rel.-9 downlink configuration*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
64-QAM	2	2x2	84

2.7.2 DC-HSUPA

Support for dual carrier HSUPA operation on adjacent uplink carriers is introduced in Release 9. This doubles the uplink peak rate to 23 Mbps for the highest used modulation 16-QAM. The uplink data rate is often more limited by the bandwidth than by UE transmit power. This is increased by multi carrier HSUPA operation. DC-HSUPA UE is able to transmit two E-DCH transport channels with 2ms TTI.

Dual-carrier HSUPA operation can only be configured together with dual-carrier HSDPA operation and the secondary uplink carrier can only be active when the secondary downlink carrier is also active. This is because the secondary downlink carrier carries information that is vital for the operation of the secondary uplink carrier. The secondary downlink carrier can, on the other hand, be active without a secondary uplink carrier being active or even configured, since all information that is vital for the operation of both downlink carriers is always only carried on the primary uplink carrier.

Configuration:

Table 2.6: *HSPA+ Rel.-9 uplink configuration*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
16-QAM	2	-	24

2.7.3 Transmit antenna array extension for non-MIMO UEs [11]

The 2x2 MIMO operation for HSDPA specified in Rel-7 allows transmission of up to two parallel data streams to a MIMO UE over a single carrier. If and when the HSDPA scheduler in the base station decides to only transmit a single stream to the UE for any reason (e.g. because the radio channel temporarily does not support dual-stream transmission), the two transmit antennas in the base station will be used to improve the downlink coverage by single-stream transmission using BF. Notably the “single-stream MIMO” transmissions can be received by a single antenna UE, whereas support for dual-stream reception requires two receive antennas in the UE, hence the feature enables single antenna UEs to benefit from the MIMO networks’ two transmit antennas.

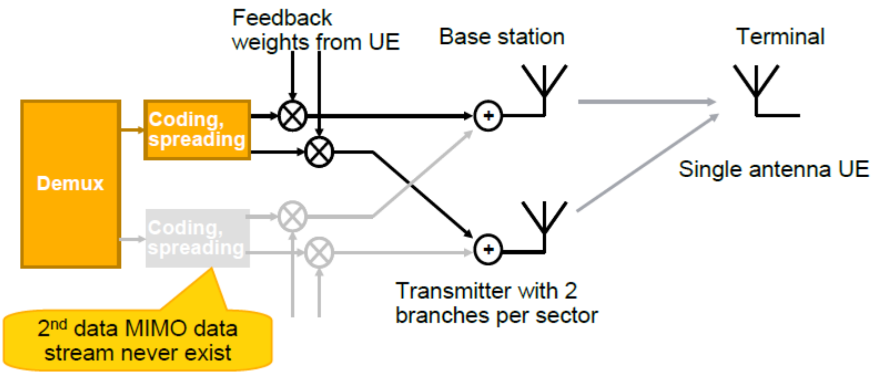

Figure 2.7: *Transmitted configuration for Single-stream MIMO [11]*

2.7.4 SON

Self Organizing Networks (SON) concept are included in the LTE (E-UTRAN) standards starting from the first release of the technology. It includes the 3GPP functions as Automatic Inventory, Automatic Software Download, Automatic Neighbour Relations (ANR) where the eNodeB can autonomously generate and manage its own intra frequency neighbour relation tables and/or sharing information with another eNodeBs. ANR is used to minimize the work required for configuration in newly deployed eNodeBs as well as to optimize configuration during operation. Correct and up-to-date neighbouring lists will increase the number of successful handovers and minimize the number of dropped calls.

SON includes also an optimization functions improving coverage, handover and interference. Mobility Robustness Optimization (MRO) which aims at reducing number of hand-over related link failures by optimally setting its parameters. It also avoids the Ping-Pong effect. Mobility Load Balancing (MLB) is related to MRO and deals with unequal traffic loads.

2.7.5 LTE Enhancements

In Release 9, LTE femtocells in the form of the Home eNodeB (HeNB) was introduced. It makes a new option of replacement of standard home WLAN.

2.7.6 MBSFN

Multimedia Broadcast Single Frequency Network (MBSFN) is a part of eMBMS mainly focused to improve broadcast services. An eNodeB can transmit the same data to multiple UE simultaneously. Also multiple eNodeBs can transmit the identical data simultaneously so that UE can receive the same data from the multiple eNodeBs in the same time. With proper synchronization of radio cells, transmitting the same content, the resulting signal will appear to a terminal as one transmission over a time-dispersive radio channel.

2.7.7 Other Enhancements

- IMS Emergency over EPS
- Location Services over EPS

2.8 Release 10

Rel.-10 was introduced in March 2011 bringing LTE-Advanced and HSPA+ enhancements.

2.8.1 4C-HSDPA [5]

By growing demand for increased data rates, support for non-contiguous four carrier HSDPA (4C-HSDPA) operation was introduced in Release 10. 4C-HSDPA enables the base station to schedule HSDPA transmissions on up to four 5 MHz carriers simultaneously. With the highest modulation scheme 64QAM and 2x2 MIMO configured on all downlink carriers this enables a peak data rate of 168 Mbps. Besides doubling the peak data rate, 4C-HSDPA operation will also double end-user data rates for a typical burst traffic model when compared to DC-HSDPA with MIMO, Release 9.

Configuration:

Table 2.7: *HSPA+ Rel.-10 downlink configuration*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
64-QAM	4	2x2	168

2.8.2 Enhanced MIMO for non-MIMO UEs [11]

The support of 2x2 MIMO Release 7 requires a second pilot channel (S-CPICH) to be sent on the second transmit antenna. This second pilot channel actually has a detrimental impact on non-MIMO users whose receiver accepts only a primary pilot channel (P-CPICH). In order to minimalize the negative impact, Release 10 introduced power balancing between the two pilot channels, so-called Virtual Antenna Matrix (VAM), to be implemented before the two transmit MIMO amplifiers.

2.8.3 LTE-Advanced

3GPP LTE Release 10 and beyond, also known as LTE-Advanced, is intended to meet the diverse requirements of advanced applications that become common in the wireless marketplace. After all it provides for backward compatibility with LTE and meets or exceed all IMT-Advanced requirements.

Release 10 introduces Carrier Aggregation (CA) to support wider bandwidths and also brings enhancements on uplink side such a single user MIMO (SU-MIMO) with two transmission modes. A single antenna port mode which is compatible with the LTE Release 8 and a multi antenna port mode which offers the possibility of a two and a four antenna port transmission. A maximum theoretical data rate is around 500 Mbps for uplink and up to 1Gbps for downlink.

2.8.4 Carrier Aggregation

With advent of Carrier Aggregation (CA) arises the requirement to support bandwidths larger than 20 MHz, currently supported in LTE, while at the same time ensuring backward compatibility with LTE. To achieve support bandwidths larger than 20 MHz, two or more component carriers are aggregated together in LTE-Advanced. An LTE-Advanced terminal with reception capability beyond 20 MHz can receive transmissions on multiple component carriers. The CA can be symmetrical (the same number of downlink and uplink component carriers) or asymmetrical, although the LTE Release

10 only supports asymmetrical CA where the number of DL carriers is grater or equal to the number of uplink carriers.

A detail of CA Release 10 is that only a single uplink Timing Advance (TA) value is supported for all component carriers. This means that the base station transceivers for different carriers should be at the same location to avoid different propagation delay.

2.8.5 Relay for LTE-Advanced [12]

The Relay Nodes (RNs) have been introduced in LTE Rel-10 to enable traffic forwarding between base station and User Equipment to improve the coverage of high data rates and to extend coverage to heavily shadowed areas in the cell or areas beyond the cell range.

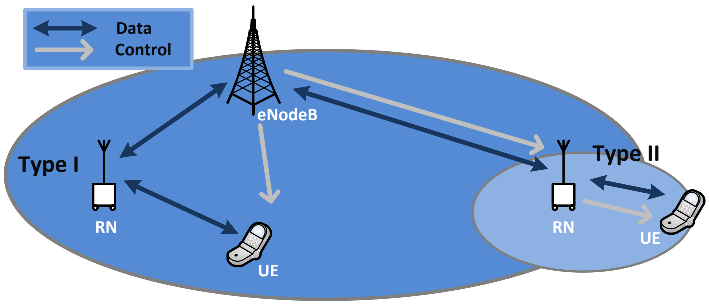

Figure 2.8: *Network scenario with two relay nodes*

By relaying both control signal and data traffic, Type-I relay works well on coverage extension for remote UEs, while, by separating control and data, Type-II relay mode is mainly used to increase data throughput for local UEs. Type-I relay carries both control signal and data traffic, and does mainly IP packet forwarding in the network layer. Compared to Type-II relay mode, it can contain multiple hops and be scheduled in both centralized and distributed way.

2.9 Release 11

2.9.1 8C-HSDPA [11]

The 8-carrier HSDPA (8C-HSDPA) extends the HSDPA up to 40 MHz bandwidth by enabling transmission simultaneously on up to eight carriers towards a single UE. The carriers do not require to be adjacent to each other on a contiguous frequency block, as it is possible to aggregate carriers together from more than one frequency band.

8-C HSDPA increase the peak DL data rate by a factor of 2 compared to 4-carrier HSDPA, and it brings similar gains as the other multi-carrier features standardized in Rel-8 to Rel-10. As a next evolution step, 4x4 MIMO can be envisioned, with the potential to yet again double the peak rate over 2x2 MIMO to 336Mbps.

Configurations:

Table 2.8: *HSPA+ Rel.-11 downlink configurations*

Modulation	Used Carrier	MIMO	Data Rate (Mbps)
64-QAM	8	2x2	336

	4	4x4	

2.9.2 MIMO extended DC-HSUPA [11]

An uplink in Dual Carrier HSPA+, Rel.-11 has been extended by MIMO stream functionality as is used in the downlink 'single stream MIMO' and 2x2 MIMO. One significant difference does exist between the uplink and downlink multi-antenna transmitter structures. Unlike in downlink, where each transmit antenna has a separate, non-pre-coded pilot channel, the uplink sends the 'primary' pilot on the DPCCH channel with the same pre-coding vector as the Tx diversity data. The secondary pilot (S-DPCCH) is sent using an orthogonal pre-coding vector, which also in MIMO case is used to transmit the secondary stream.

Configuration:

Table 2.9: *HSPA+ Rel.-11 uplink configuration*

Modulation	Used Carriers	MIMO	Data Rate (Mbps)
64-QAM	2	2x2	72

2.9.3 Coordinated Multipoint

In Release 11 is introduced a tool to improve coverage and system efficiency called Coordinated Multipoint (CoMP) transmission and reception. The main idea of CoMP is as follows: when a UE is in the cell-edge region, it may be able to receive signals from multiple cell sites and the UE's transmission may be received at multiple cell sites regardless of the system load. Given that, if the signalling transmitted from the multiple cell sites is coordinated, the DL performance can be increased significantly. This coordination can be simple as in the techniques that focus on interference avoidance or more complex as in the case where the same data is transmitted from multiple cell sites. For the UL, since the signal can be received by multiple cell sites, if the scheduling is coordinated from the different cell sites, the system can take advantage of this multiple reception to significantly improve the link performance.

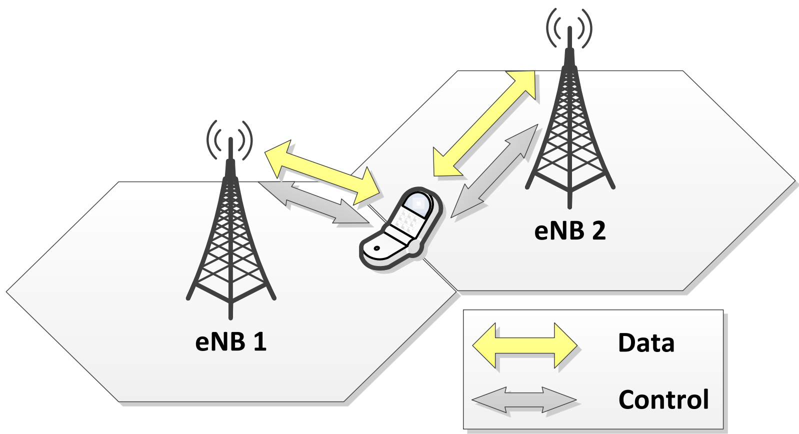

Figure 2.9: *Example of Coordinated Multipoint functionality*

2.9.4 Carrier Aggregation Enhancements

Release 11 supports inter-band Carrier Aggregation where the component carriers are located in different frequency bands. This proves to be very beneficial for operators having LTE frequencies in different bands. Also supports a multiple uplink Timing Advances and other enhancements to support non-collocated cells, e.g. multiple uplink power control instances or improved sounding reference symbols. One of the key scenarios is a use of Remote Radio Heads (RRHs) connected via fibre to a central baseband unit as shown in Figure 2.10. Another variation of this scenario would be that macro and small cells both use the same frequencies F1 and F2 in parallel. In this case inter-cell interference coordination will be required.

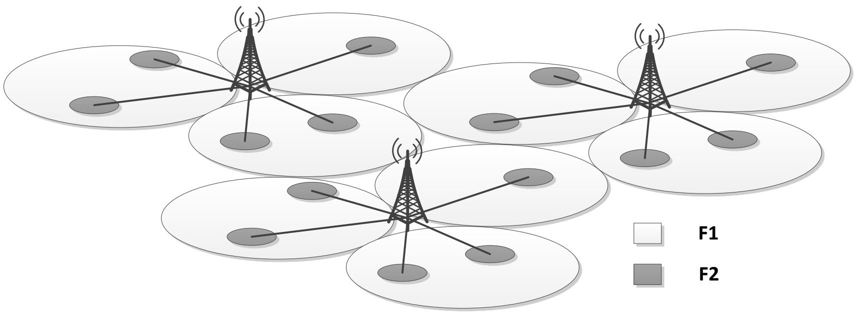

Figure 2.10: *Heterogeneous network using Remote Radio Heads*

2.10 Release 12

Publishing of Release 12 is expected in the second quarter of 2014. Many parts of this release are in a “Study Work” phase and it may not be included in it.

2.10.1 3D-MIMO [13]

By continued progress of antenna technologies, enhancements of the macro cell eNBs can be realized mostly by exploiting an increased frequency reuse and reduced interference in the spatial domain.

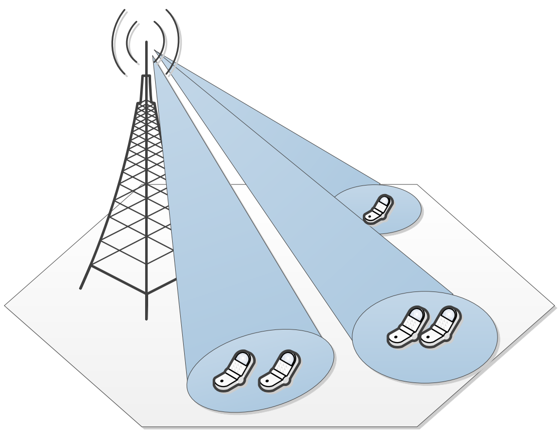

Figure 2.11: *3D-MIMO Beam Forming*

Due to the reuse of the existing cell sites and transport network, operators are provided attractive means of capacity enhancements at reasonable costs. Potential changes to the specifications will mostly impact Channel State Information (CSI) feedback. Amongst others Pre-coding Matrix Indicator (PMI) codebook enhancements might allow for a finer spatial domain granularity and might support different eNB antenna configurations. New CSI feedback modes might also be introduced. There is also a Rel.12 study item that will standardize a new 3D channel model to allow for accurate system-level simulations of such antenna technologies, shown in Figure 2.11.

2.10.2 **Lean Carrier Application [14]**

In such a heterogeneous deployment, low-power nodes provide high capacity and enhanced user data rates locally while the macro nodes provide reliable wide-area coverage. The Lean Carrier fits nicely into the Release 12 concept of dual connectivity, where the UE maintains its connection to the macro node while a simultaneous connection to a low-power node can be added. The legacy LTE connection to the macro can be used for system information and basic control signalling, while the Lean Carrier connection to the low-power node can be used for high-capacity data transmissions. Figure 2.12 illustrates such a small cell scenario using dual connectivity where the terminal is connected to the macro node using a legacy LTE carrier and to the low-power node through a Lean Carrier. A types of a Lean Network application are listed in a Table 2.10.

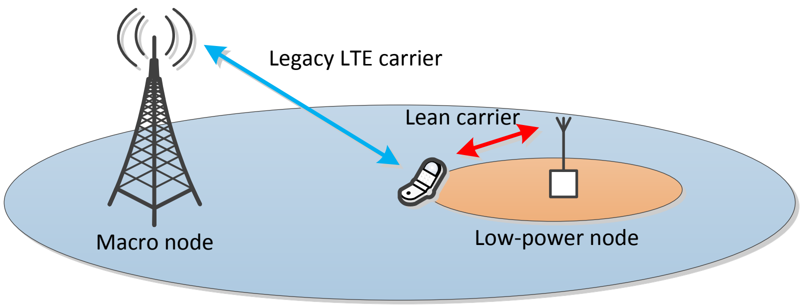

Figure 2.12: *Scenario where the UE is connected to macro node and low-power node*

Table 2.10: *New carrier application types*

Type:	**Pros:**	**Cons:**
Standalone and Backward Compatible	Accessible by legacy UE supporting new bands	Limited for optimization
Standalone and non-Backward Compatible	Larger space for optimization	Legacy UE cannot access a lean carrier
Non-Standalone and non-Backward Compatible	The largest space for optimization	Legacy UE cannot access a lean carrier Cannot work without the coverage of legacy carrier

2.10.3 LTE-Direct

The LTE-Direct is separated to two main phases: Device to device (D2D) discovery and D2D communication. The application for the first phase is to enable devices to “express” their identity to other UE in the local area. This can be used for a variety of purposes including location based advertising.

The second phase of D2D has all kinds of uses including public safety involving communication in the absence of a network.

2.10.4 Other Enhancements

- Higher order modulation – 256QAM
- Dynamic TDD
- LTE and WiFi/HSDPA interworking

2.11 Summary

The evolution of mobile networks has risen dynamically in last decade bringing a new technologies, higher data rates and capacity, and more effective utilization of frequency spectrum. Until release 8, a mobile networks were only based on a CDMA technology which has been successfully evolved for its maximum utilization of frequency spectrum according to user data rate.

Since release 8, LTE networks have taken place as a next evolution step. By a variable bandwidth and high data rate, it has also found an application in small areas such home networks, etc.

A System Architecture Evolution is considered as the biggest milestone in telecommunication networks evolution. It brings a new full-IP core structured by the easiest way. A success of this architecture is built in a wide range of applications, not even in telecommunication sphere.

In 2011, the LTE have been succeed by LTE-Advanced reaching IMT-Advanced requirements issued by the International Telecommunication Union (ITU). It becomes the new international standard and opens ways for future improvements.

The evolution is also about features such a usage of MBMS, Location Services, VoIP and many other technologies to satisfy the needs of end-users.

A building and applying of new technologies is also very expensive since LTE networks require a fibre backbone networks and X2 connections between neighbour eNodeBs.

3 UMTS (Rel.7) & LTE/SAE (Rel.10) – Physical Layers Comparison [6]

3.1 Overview [9]

3.1.1 HSPA+

Structure of HSPA Rel.-7 is based on previous model of UMTS network. Data flow is split onto signalling and user data incoming from a core network. The user data, for example in the form of IP packets, are first processed by the Packet Data Convergence Protocol (PDCP) which performs (optional) header compression. The Radio Link Protocol (RLC) is, among others, responsible for segmentation of the IP packets into smaller units known as RLC Protocol Data Units (RLC PDUs) and pushed to MAC layer by determined logical channels. The MAC layer can multiplex data from multiple logical channels. It is also responsible for determining the Transport Format of the data sent to the next layer, the physical layer. This interface is specified through so-called Transport Channels over which data in the form of transport blocks are transferred. In Release 7, there is a Transmission Time Interval (TTI) length 2ms. In each TTI one or several transport blocks are fed from the MAC layer to the physical layer, which performs coding, interleaving, multiplexing, spreading, etc., prior to data transmission.

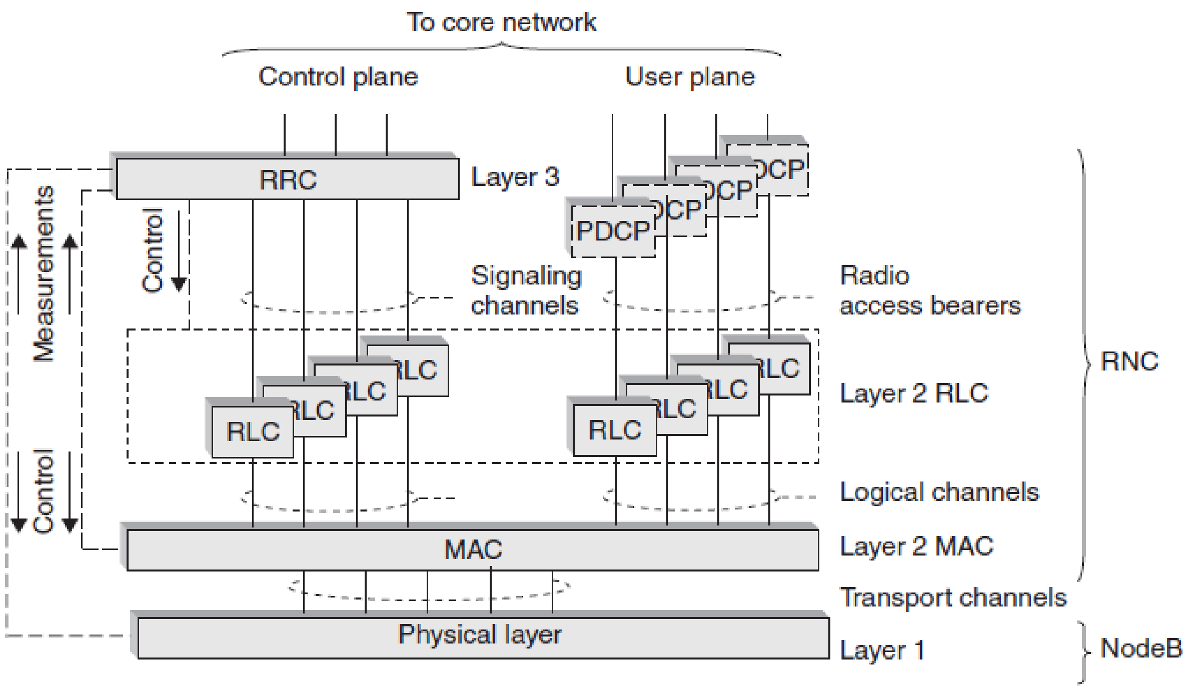

Figure 3.1: *Overview of HSPA Rel.-7 protocol structure [9]*

3GPP Release 7 supports, as a first, MIMO technology enables data rate up to 28Mbps. To support dual-stream transmission, the HS-DSCH (High Speed Downlink Shared Channel) is modified to support up to two transport blocks per TTI. Each transport block represents one stream. A CRC is attached to each of the transport blocks and each transport block is individually coded. This is illustrated in Figure 3.3. Since two transport blocks are used in case of multi-stream transmission, HSDPA-MIMO is a multi-code word scheme and allows for a successive interference-cancellation receiver in the UE.

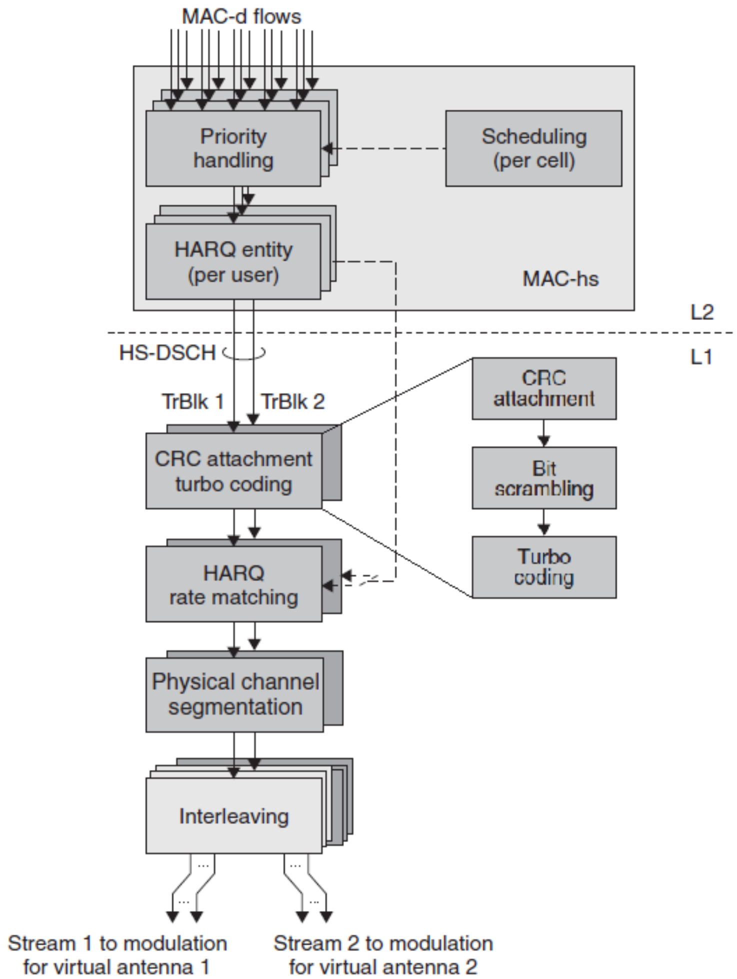

Figure 3.2: *Physical layer processing for HS-DSCH [9]*

Each stream is subject to the same physical-layer processing in terms of coding, spreading and modulation as the corresponding single-layer HSDPA case. After coding, spreading, and modulation, linear pre-coding is used before the result is mapped to the two transmit antennas. Even if only a single stream is transmitted, it can be beneficial to exploit both transmit antennas by using transmit diversity.

In essence, this can be seen as a simple form of beam-forming. Furthermore, the pre-coding attempts to pre-distort the signal such that the two streams are (close to) orthogonal at the receiver. This reduces the interference between the two streams and lessens the burden on the receiver processing. The physical-layer processing for each stream is identical to the single-stream case, up to and including spreading.

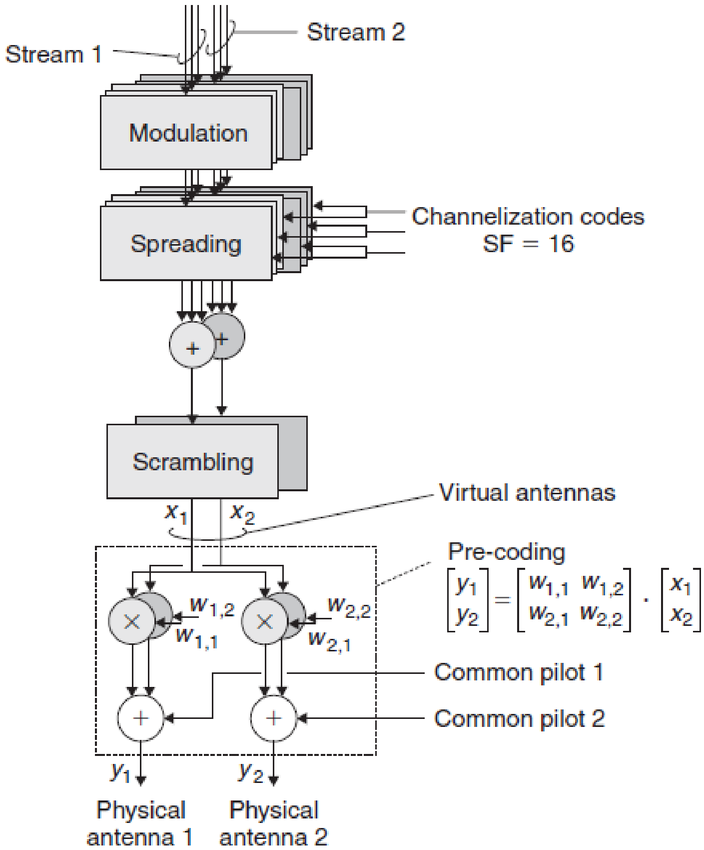

Figure 3.3: *Physical layer processing for HS-DSCH [9]*

3.1.2 **LTE-A**

Similar to WCDMA/HSPA, as well as to most other modern communication systems, the processing specified for LTE is structured into different protocol layers. A general overview of the LTE protocol architecture for the downlink is illustrated in Figure 3.2. It is important to note that not all the entities illustrated in Figure 3.2 are applicable in all situations. For example, neither MAC scheduling nor hybrid ARQ with soft combining is used for broadcast of system information. Furthermore, the LTE protocol structure related to uplink transmissions is similar to the downlink structure.

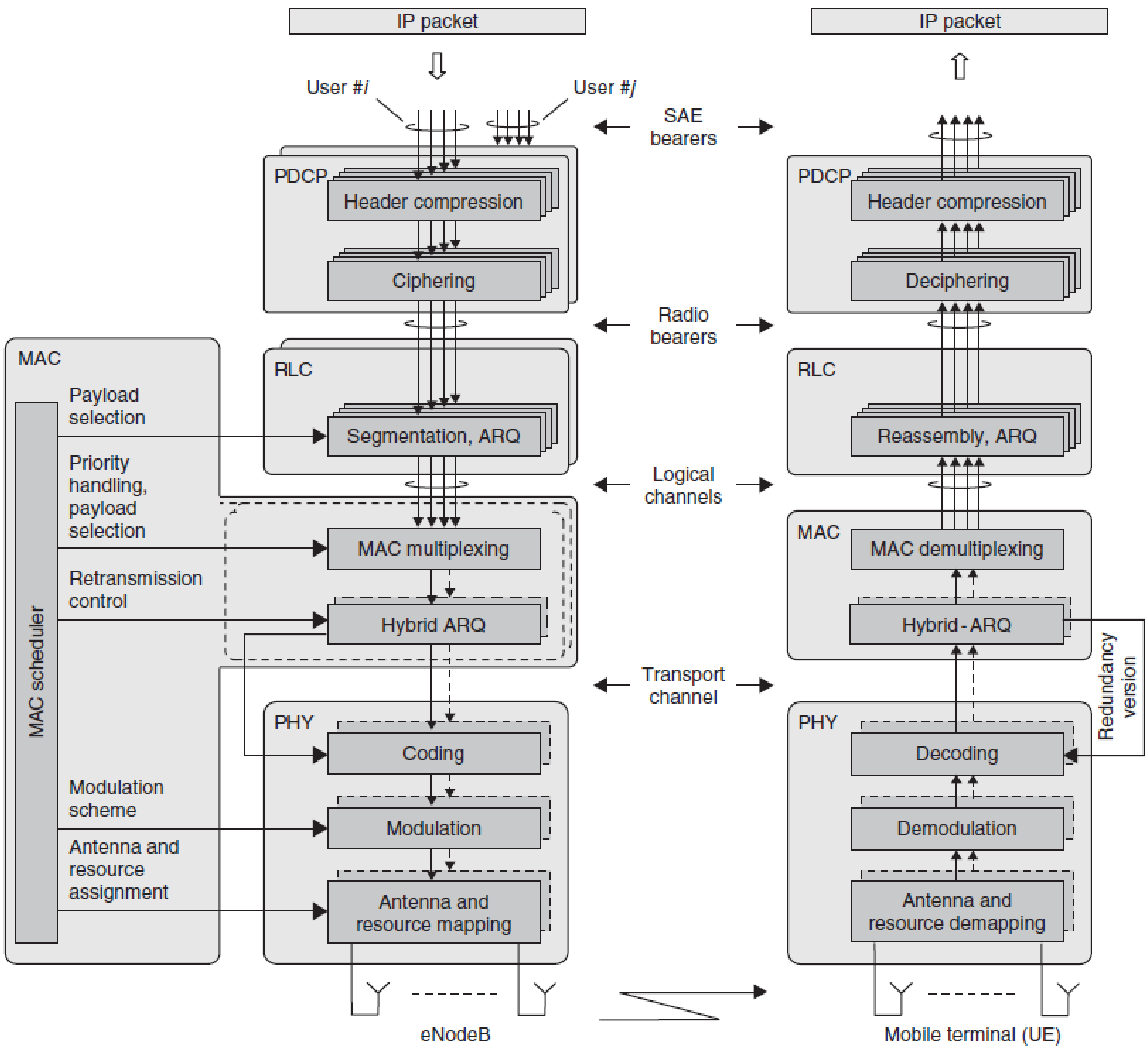

Figure 3.4: *Overview of LTE protocol structure [9]*

The physical layer offers services to the MAC layer in the form of transport channels. In the downlink, the DL-SCH is the main channel for data transmission and the processing for Paging Channel (PCH) and Multicast Channel (MCH) is similar. In each TTI, there is at most one (two in case of spatial multiplexing) transport blocks.

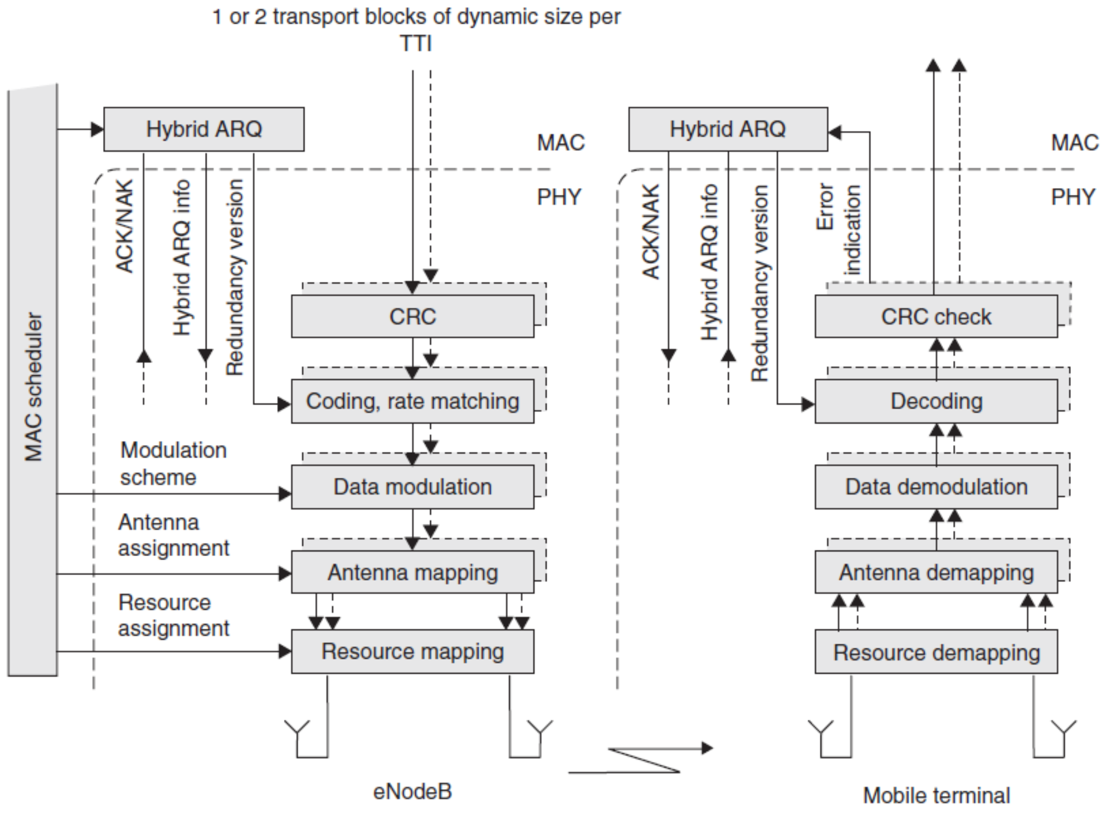

Figure 3.5: *Physical layer processing for DL-SCH [9]*

The downlink physical-layer processing of transport channels consists of the following steps:

- CRC insertion: 24 bit CRC for PDSCH
- Channel coding: Turbo coding based on QPP inner interleaving with trellis termination
- Physical-layer hybrid-ARQ processing
- Channel interleaving
- Scrambling: transport-channel specific scrambling on DL-SCH, BCH, and PCH. Common MCH scrambling for all cells involved in a specific MBSFN transmission
- Modulation: QPSK, 16QAM, and 64QAM
- Layer mapping and pre-coding
- Mapping to assigned resources and antenna ports

3.2 CRC attachment [15,16]

Error detection is provided on transport blocks through a Cyclic Redundancy Check (CRC). The size of the CRC is 24, 16, 12, 8 or 0 bits and it is signalled from higher layers what CRC size that should be used for each transport channel (TrCH).

3.2.1 HSPA+

The entire transport block is used to calculate the CRC parity bits for each transport block. A number of parity bits can take the values 24, 16, 12, 8, or 0 depending on what is signalled from higher layers. If no transport blocks are input to the CRC calculation, no CRC attachment shall be done. If transport blocks are input to the CRC calculation and the size of a transport block is zero, CRC shall be attached, i.e. all parity bits equal to zero.

All transport blocks in a TTI are serially concatenated. If the number of bits in a TTI is larger than the maximum size of a code block in question, then code block segmentation is performed after the concatenation of the transport blocks. The maximum size of the code blocks depends on whether convolutional coding or turbo coding is used for the TrCH.

The maximum size of the code blocks:

- Convolutional coding – 504
- Turbo coding – 5114

3.2.2 LTE-A

The CRC attachment for LTE-Advanced is very similar. Each transport block is protected with checksum calculated as cyclic redundancy check. The number of parity bits is 24, 16, 8 and 0, although there are two different cyclic generator polynomials for length 24. The CRC output bit sequence is denoted by $b_0, b_1, b_2, \ldots, b_{B-1}$, where B is a sum of a size of input sequence and the number of parity check (24, 16, 8, 0).

The input bit sequence to the code block segmentation is denoted by $b_0, b_1, b_2, \ldots, b_{B-1}$, where $B > 0$. If B is larger than the maximum code block size, segmentation of the input bit sequence is performed and an additional CRC sequence of length 24 bits is attached to each code block.

The maximum size of code blocks is 6144.

3.3 Channel coding [15,16]

The forward error check that is applied to the transport block with its CRC is based on three available coding algorithms: turbo coding rate 1/3, convolutional coding rate 1/2 or 1/3 and a 32-to-2 block coding only used by some control information.

3.3.1 Convolutional coding

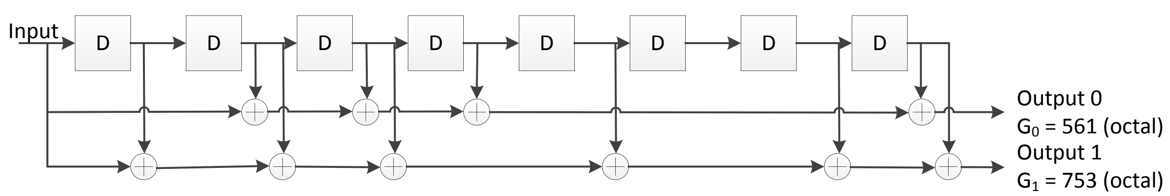

Figure 3.6: *Rate 1/2 convolutional coder with constraint length 9 [15]*

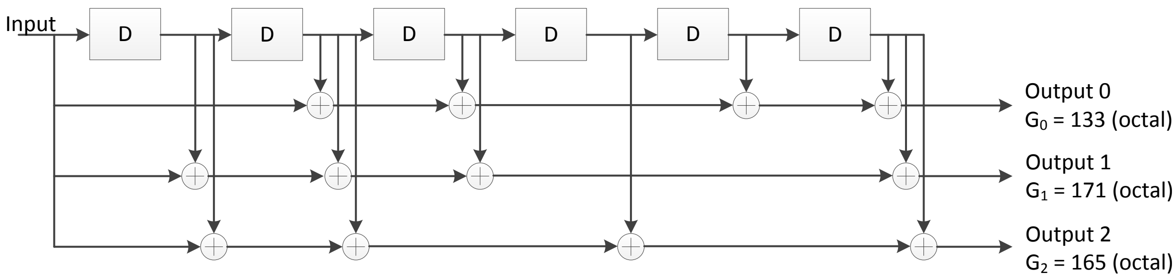

Figure 3.7: *Rate 1/3 convolutional coder with constraint length 7 [16]*

3.3.2 Turbo coding

The scheme of turbo encoder is a Parallel Concatenated Convolutional Code (PCCC) with two 8-state constituent encoders and one turbo code internal interleaver. The coding rate of turbo encoder is 1/3. The structure of turbo encoder is illustrated in Figure 3.8.

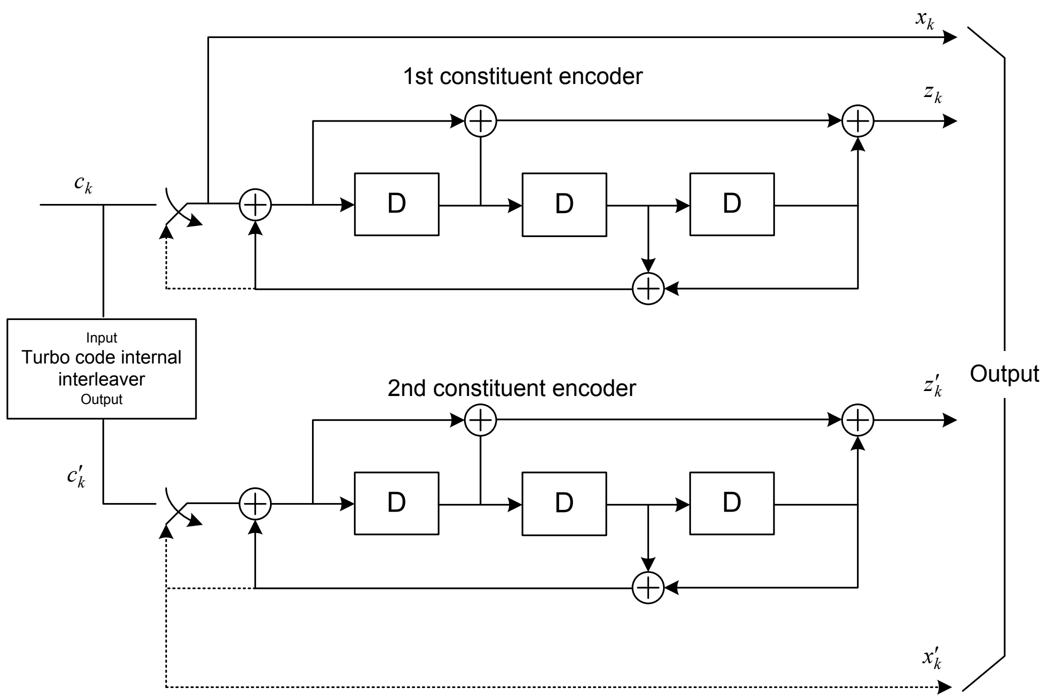

Figure 3.8: *Structure of rate 1/3 turbo encoder [16]*

The bits input to the turbo encoder is C_k, and the bits output from the first and second 8-state constituent encoders are Z_k and Z'_k,. The bits output from the turbo code internal interleaver represents C'_k, and these bits are to be the input to the second 8-state constituent encoder.

This structure is the same for HSPA+ and LTE-Advanced.

3.3.3 HSPA+

HSPA+ uses only a convolutional coding and a turbo coding as shown in Table 3.1, below.

Convolutional codes with constraint length 9 and coding rates 1/2 and 1/3 are defined. Eight tail bits with binary value 0 shall be added to the end of the code block before encoding. The initial value of the shift register of the coder shall be "all 0" when starting to encode the input bits.

Table 3.1: *Usage of channel coding scheme and coding rate*

<table>
<tr><th>Transport Channels</th><th>Coding scheme</th><th>Coding rate</th></tr>
<tr><td>BCH</td><td rowspan="5">Convolutional coding</td><td rowspan="3">1/2</td></tr>
<tr><td>PCH</td></tr>
<tr><td>RACH</td></tr>
<tr><td rowspan="3">DCH, FACH</td><td>1/3, 1/2</td></tr>
<tr><td>Turbo coding</td><td>1/3</td></tr>
</table>

3.3.4 LTE-A

Usage of coding scheme and coding rate for the different types of TrCH is pictured in Table 3.2. Number of encoded bits per output stream *D* is equal to number of bits to encode using a tail biting convolutional coding with rate 1/3. For turbo coding with rate 1/3:

$$D = K+4 \quad (3.1)$$

Table 3.2: *Usage of channel coding scheme and coding rate for TrCHs*

<table>
<tr><th>Transport Channels</th><th>Coding scheme</th><th>Coding rate</th></tr>
<tr><td>UL-SCH</td><td rowspan="4">Turbo coding</td><td rowspan="4">1/3</td></tr>
<tr><td>DL-SCH</td></tr>
<tr><td>PCH</td></tr>
<tr><td>MCH</td></tr>
<tr><td>BCH</td><td>Tail biting convolutional coding</td><td>1/3</td></tr>
</table>

3.4 Rate Matching [15,16]

Rate matching means that bits on a transport channel are repeated or punctured. Higher layers assign a rate-matching attribute for each transport channel. The rate matching attribute is used when the number of bits to be repeated or punctured is calculated.

3.4.1 **HSPA+**

The number of bits on a transport channel can vary between different transmission time intervals. In the downlink, the transmission is interrupted if the number of bits is lower than maximum. When the number of bits between different transmission time intervals in uplink is changed, bits are repeated or punctured to ensure that the total bit rate after TrCH multiplexing is identical to the total channel bit rate of the allocated dedicated physical channels.

Figure 3.9 shows a structure of rate matching for turbo encoded transport channels.

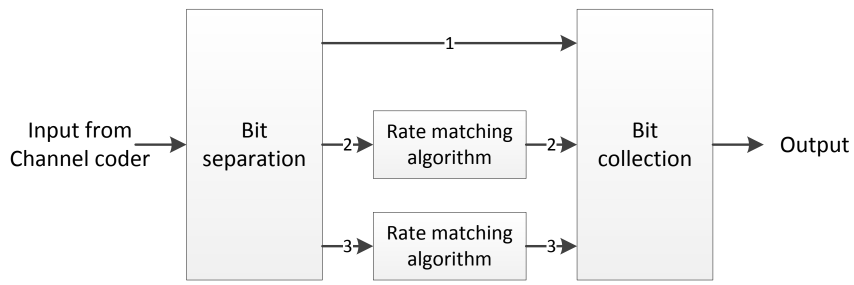

Figure 3.9: *Puncturing of turbo encoded TrCHs [15]*

The rest of transport channels uses rate matching in Figure 3.10.

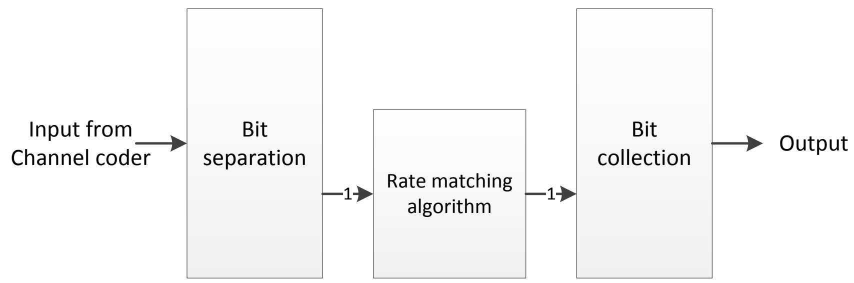

Figure 3.10: *Rate matching for convolutionally encoded TrCH and for turbo encoded TrCHs with repetition [15]*

3.4.1.1 ***Bit separation***

The systematic bits of turbo encoded TrCHs shall not be punctured, the other bits may be punctured. The systematic bits, first parity bits and second parity bits in the bit sequence input to the rate matching block are therefore separated into three sequences of equal lengths.

The first sequence contains:

- All of the systematic bits that are from turbo encoded TrCHs.
- Some of the systematic, first parity and second parity bits that are for trellis termination.

The second sequence contains:

- All of the first parity bits that are from turbo encoded TrCHs.
- Some of the systematic, first parity and second parity bits that are for trellis termination.

The third sequence contains:

- All of the second parity bits that are from turbo encoded TrCHs.
- Some of the systematic, first parity and second parity bits that are for trellis termination.

Puncturing is applied only to the second and third sequences.

The bit separation function is transparent for convolutionally encoded TrCHs and for turbo encoded TrCHs with repetition.

3.4.1.2 ***Rate matching algorithm***

The rate matching algorithm works sequentially where checks if puncturing is to be performed, does its puncturing, error update and a bit repeat check.

3.4.1.3 ***Bit collection***

Bit collection is the inverse function of the separation. After bit collection, the bits indicated as punctured are removed. Also bits with value not belonging to set {0,1} are removed from the bit sequence.

3.4.2 LTE-A

The rate matching for turbo coded transport channels is defined per coded block and consists of interleaving the three information bit streams followed by the collection of bits and the generation of a circular buffer as depicted in Figure 3.11.

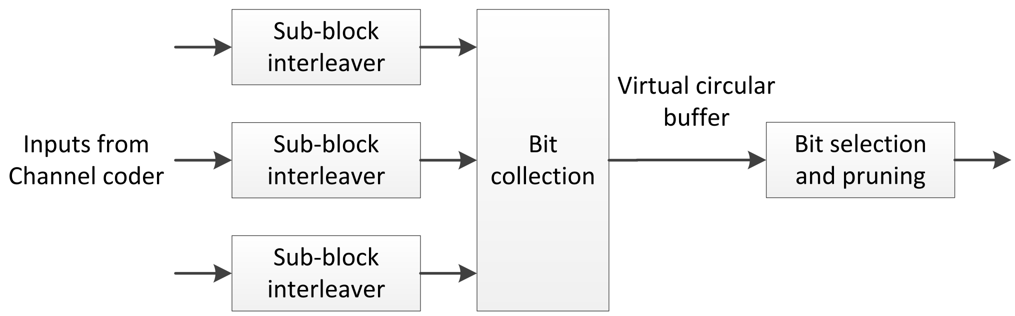

Figure 3.11: *Rate matching for turbo coded and convolutionally coded TrCHs [16]*

3.4.2.1 ***Sub-block interleaver***

A sub-block interleaver creates a matrix with exactly 32 columns. The number of rows is determined by formula 3.2,

$$D \leq (R \cdot C) \qquad (3.2)$$

where

D….number of input bits

R….number of rows

C….number of columns (32).

Then the matrix is filled up by the bit sequence algorithm and the inter-column permutation is performed. The output of the block interleaver is the bit sequence read out column by column from the inter-column permuted matrix.

3.4.2.2 ***Bit collection, selection and transmission***

The circular buffer is created from output of interleavers sorted in a row as the rate matching output bit sequence.

3.5 Interleaving and Code block concatenation

3.5.1 HSPA+

The interleaving is a block interleaver with inter-column permutations very similar to Sub-block interleaver in LTE. The input bit sequence is put into the matrix, where number of columns reflects the size of TTI. The number of rows is determined from number of bits and the inter-column permutation for the matrix is performed.

3.5.2 LTE-A

The code block concatenation consists of sequentially concatenating the rate matching outputs for the different code blocks.

3.6 Physical channel processing

3.6.1 HSPA+ [17]

3.6.1.1 ***Downlink***

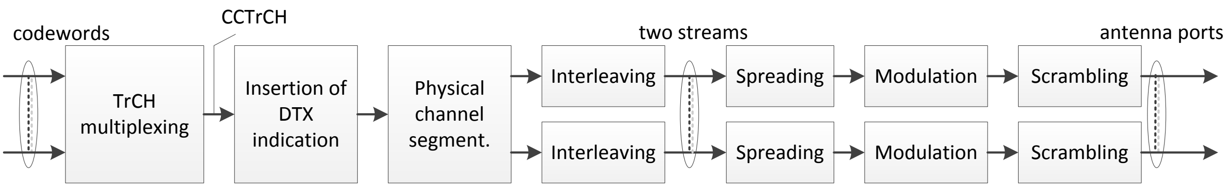

Figure 3.12: *Downlink physical channel processing of HSPA+*

Transport channel multiplexing

Every 10ms, one radio frame from each TrCH is delivered to the TrCH multiplexing. These radio frames are serially multiplexed into a Coded Composite Transport Channel (CCTrCH).

Insertion of DTX indication

In the downlink, DTX is used to fill up the radio frame with bits. The insertion point of DTX indication bits depends on whether fixed or flexible positions of the TrCHs in the radio frame are used. It is up to the UTRAN to decide for each CCTrCH whether fixed or flexible positions are used during the connection. DTX indication bits only indicate when the transmission should be turned off, they are not transmitted.

Physical channel segmentation

When more than one PhCH is used, physical channel segmentation divides the bits among the different PhCHs. For all modes, some bits of the input flow are mapped to each code until the number of bits on the code is equal to number of bits in one radio frame. All bits of the input flow are taken to be mapped to the codes. A formula 3.3 shows a relation

$$U = (X / P) \tag{3.3}$$

where

U….number of bits in one radio frame

X….number of bits input to the PhCH segmentation

P….number of PhCH.

Interleaving

Interleaving creates a matrix with 30 columns and number of rows determined by formula 3.3. Then, the matrix is filled up by incoming bits row by row and the inter-column permutation is performed.

$$U \leq (R \cdot C) \tag{3.4}$$

where

U….number of bits in one radio frame

R….number of rows

C….number of columns (30)

Spreading

Figure 3.13 illustrates the spreading operation for all physical channel except SCH. The spreading operation includes a modulation mapper stage followed by a channelization stage, an IQ combining stage and a scrambling stage. The non-spread downlink physical channels, except SCH, AICH, E-HICH and E-RGCH consist of a sequence of 3-valued digits taking the values 0, 1 and DTX (Only channels supporting DTX)

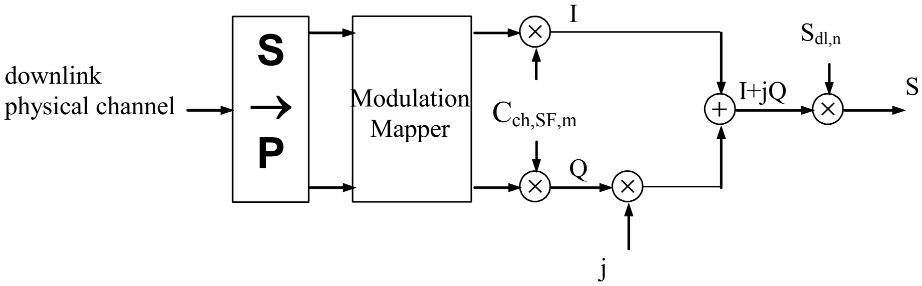

Figure 3.13: *Spreading operation [17]*

Modulation

Input PhCHs are modulated using modulation QPSK, 16QAM or 64QAM as defined in Table 3.3.

Table 3.3: *Usage of modulation mapping for different PhCHs*

Physical channels	**Used modulation**
HS-PDSCH S-CCPCH	QPSK, 16QAM or 64QAM
All other channels	QPSK

Channelization and Scrambling

The channelization codes - Orthogonal Variable Spreading Factor (OVSF) codes that preserve the orthogonality between downlink channels of different rates and spreading factors (SF).

The channelization code for the Primary CPICH is fixed to Cch,256,0 and the channelization code for the Primary CCPCH is fixed to Cch,256,1.The channelization codes for all other physical channels are assigned by UTRAN.

Table 3.4: *Spreading factor definition for different PhCHs*

Physical channels	**SF**
F-DPCH	256
HS-PDSCH	16
HS-SCCH	128

OVSF codes shall be allocated in such a way that they are positioned in sequence in the code tree. For E-HICH and for E-RGCH, the spreading factor shall always be 128. In each cell, the E RGCH and E-HICH assigned to a UE shall be configured with the same channelization code. For E-AGCH, the spreading factor shall always be 256.

At the end, a scrambling code is added to the sequence. A total number of scrambling codes is 2^{18}-1, numbered 0 – 262142. By using the scrambling code, UE can separate signals coming simultaneously from many different NodeB.

3.6.1.2 ***Uplink***

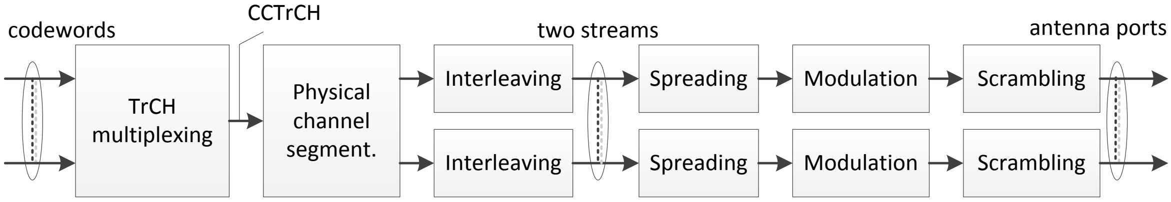

Figure 3.14: *Uplink physical channel processing of HSPA+*

Transport channel multiplexing

A TrCH multiplexing is the same as used in downlink, Section 3.6.1.1.

Physical channel segmentation

A PhCH segmentation is the same as described in Section 3.6.1.1.

Interleaving

An interleaving is the same as described in Section 3.6.1.1.

Spreading

Figure 3.15 illustrates the principle of the spreading of uplink dedicated physical channels. In case of BPSK modulation , the binary input sequences of all physical channels are converted to real valued sequences, i.e. the binary value "0" is mapped to the real value +1, the binary value "1" is mapped to the real value –1, and the value DTX (HS-DPCCH only) is mapped to the real value 0.

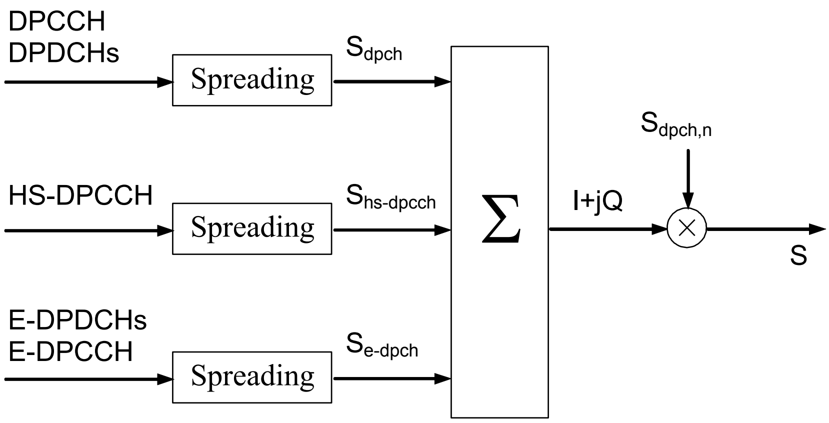

Figure 3.15: *Uplink spreading processing of HSPA+*

Channelization and Scrambling

An OVSF codes preserve the orthogonality between a user’s different physical channels. Channelization codes depends on the spreading factor.

All uplink physical channels shall be scrambled with a complex-valued scrambling code. The dedicated physical channels may be scrambled by either a long or a short scrambling code. The PRACH message part shall be scrambled with a long scrambling code. There are 224 long and 224 short uplink scrambling codes. Uplink scrambling codes are assigned by higher layers.

Modulation

There is a 16QAM mapping used in uplink side with modulation chip rate 3.84 Mcps.

3.6.2 LTE-A [18]

3.6.2.1 Downlink

Scrambling

For each codeword, the block of bits shall be scrambled prior to modulation. The scrambling sequence generator shall be initialised at the start of each sub-frame, where the initialisation value depends on the transport channel type. Up to two codewords can be transmitted in one sub-frame.

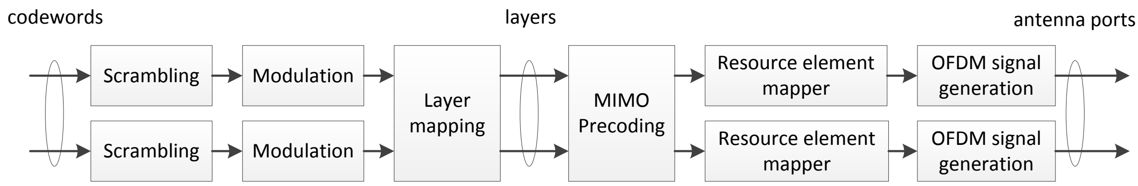

Figure 3.16: *Downlink physical channel processing of LTE-A [18]*

Modulation

For each codeword, the block of scrambled bits shall be modulated using the modulation schemes QPSK, 16QAM or 64QAM applicable for PDSCH and PMCH.

Layer mapping

The complex-valued modulation symbols for each of the codewords to be transmitted are mapped onto one or several layers. For transmission on a single antenna port, a single layer is used. For spatial multiplexing, the number of layers is less than or equal to the number of antenna ports used for transmission of the physical channel. The case of a single codeword mapped to multiple layers is only applicable when the number of cell-specific reference signals is four or when the number of UE-specific reference signals is two or larger. Layer mapping has also specified algorithms for transmit diversity.

Precoding

For transmission on a single antenna port, precoding only forwards input bit stream to the resource mapper. Precoding for spatial multiplexing using antenna ports with cell-specific reference signals is only used in combination with layer mapping for spatial multiplexing. Spatial multiplexing supports two or four antenna ports and the set of antenna ports used is {0,1} or {0,1,2,3}. There is also precoding for transmit diversity. It is only used in combination with layer mapping for transmit diversity and it is defined for two and four antenna ports as well.

Mapping to physical resources

For each of the antenna ports used for transmission of the physical channel, the block of complex-valued symbols shall conform to the downlink power allocation and be mapped in sequence which meet all of the following criteria:

- they are in the physical resource blocks corresponding to the virtual resource blocks assigned for transmission
- they are not used for transmission of PBCH, synchronization signals, cell-specific reference signals, MBSFN reference signals or UE-specific reference signals
- they are assumed by the UE not to be used for transmission of CSI reference signals and the DCI associated with the downlink transmission uses the Cell Radio Network Temporary Identifier (C-RNTI) or semi-persistent C-RNTI.

3.6.2.2 ***Uplink***

Scrambling

For each codeword, the block of bits shall be scrambled with a UE-specific scrambling sequence prior to modulation. The scrambling sequence generator shall be initialised with at the start of each sub-frame. Up to two codewords can be transmitted in one sub-frame.

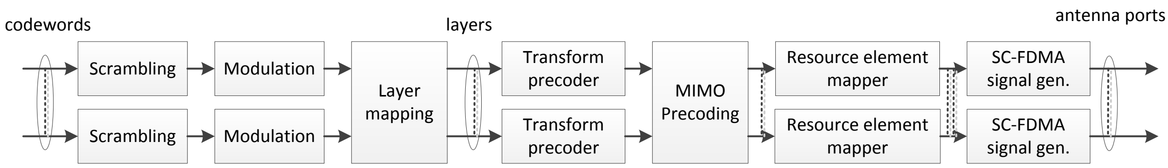

Figure 3.17: *Uplink physical channel processing of LTE-A [18]*

Modulation

For each codeword, the block of scrambled bits shall be modulated resulting in a block of complex-valued symbols. The modulation mapping applicable for Physical Uplink Shared Channel (PUSCH) are QPSK, 16QAM and 64QAM.

Layer mapping

The complex-valued modulation symbols for each of the codewords to be transmitted are mapped onto one or two layers. For transmission on a single antenna port, a single layer is used. For spatial multiplexing, the number of layers is less than or equal to the number of antenna ports used for transmission of the PUSCH. The case of a single codeword mapped to multiple layers is only applicable when the number of antenna ports used for PUSCH is four.

Transform precoding

For each layer, the block of complex-valued symbols is divided into sets, each corresponding to one SC-FDMA symbol.

Precoding

For transmission on a single antenna port, precoding only forwards input bit stream to the resource mapper. For spatial multiplexing, precoding is only used in combination with layer mapping for spatial multiplexing. Spatial multiplexing supports 2 or 4 antenna ports of sets {20,21} or {40,41,42,43}.

Mapping to physical resources

For each antenna port used for transmission of the PUSCH in a sub-frame the block of complex-valued symbols shall be multiplied with the amplitude scaling factor in order to conform to the transmit power and mapped to physical resource blocks on antenna port and assigned for transmission of PUSCH. The mapping to resource elements corresponding to the physical resource blocks assigned for transmission and:

- not used for transmission of reference signals (SRS)
- not part of the last SC-FDMA symbol in a sub-frame, if the UE transmits SRS in the same sub-frame
- not part of the last SC-FDMA symbol in a sub-frame configured with cell-specific SRS, if the PUSCH transmission partly or fully overlaps with the cell-specific SRS bandwidth
- not part of an SC-FDMA symbol reserved for possible SRS transmission in a UE-specific aperiodic SRS sub-frame

3.7 Antenna Mapping

3.7.1.1 HSPA+

In HSPA release 7, one superframe contains 72 radio frames carrying user data and control information. The radio frame, show in Figure 3.18, is separated onto 5 subframes of 2ms length. Each subframe is divided onto 3 slots least 0.667ms. The number of bits in slot is variable depending on used modulation. A timing relations of channels is also included.

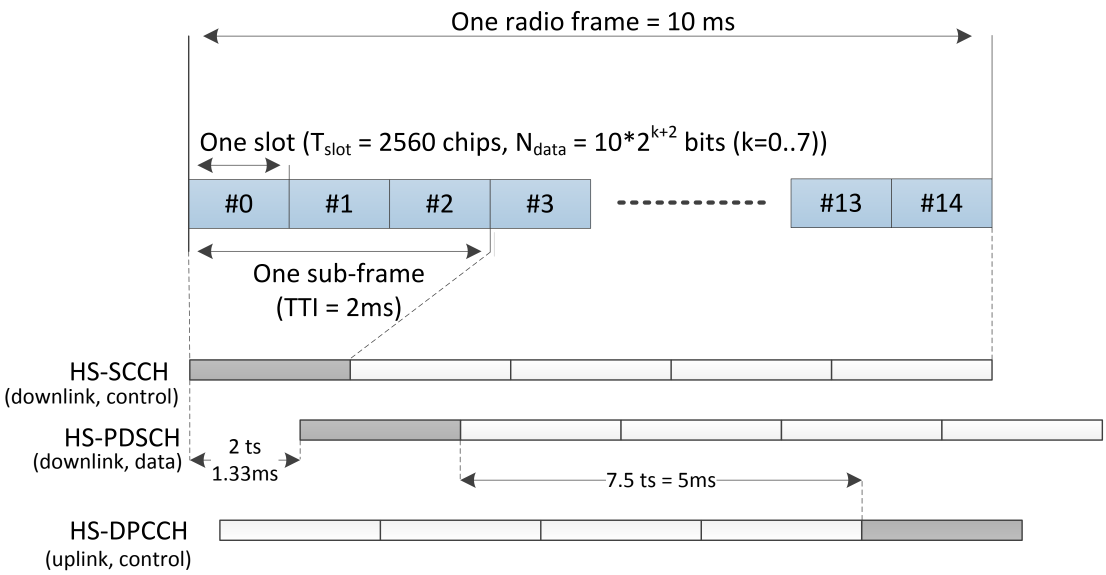

Figure 3.18: *HSPA+ radio frame structure*

An example of spreading is illustrated in Figure 3.19. A scheduler works variably, depends to actual needs. In case of MIMO usage, there is a one stream for each antenna port.

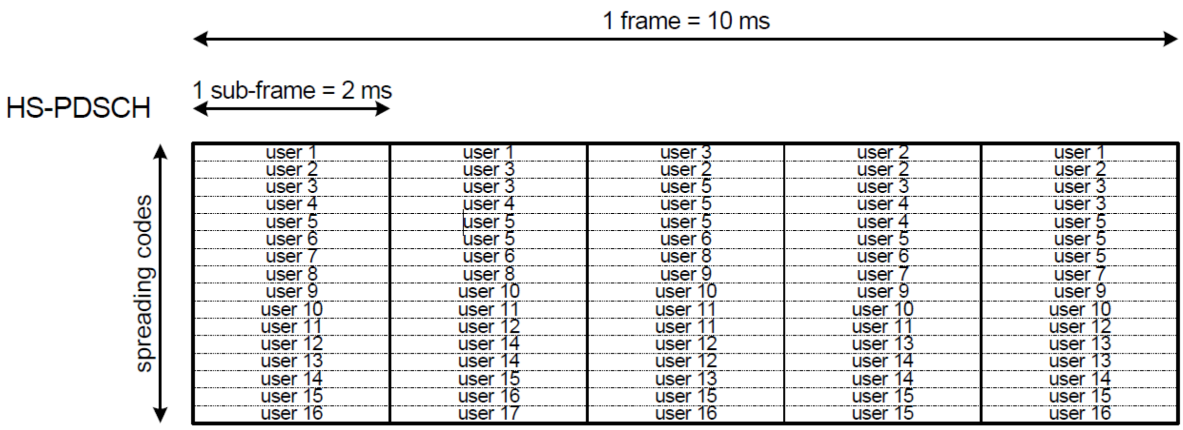

Figure 3.19: *Example of spreading*

Main HSPA+ parameters are listed in Table 3.5. HSPA+ uses the same Code Division Multiple Access for downlink and uplink and as a last release 7 offers its services only in 5MHz bandwidth. Compare to LTE, HSPA+ does not use any cyclic prefix. Modulation is 16 or 64 state QAM depends to actual configuration and MIMO usage. This is available only for downlink transmission and reception.

Table 3.5: *HSPA+ parameters*

Access Scheme	DL	W-CDMA
	UL	W-CDMA
Bandwidth		5 MHz
Minimum TTI		2ms
Cyclic prefix length	Short	-
	Long	-
Modulation		16QAM, 64QAM
Spatial multiplexing		Single layer for UL per UE Up to 2 layers for DL per UE SU-MIMO only supported for DL

3.7.1.2 ***LTE***

Frame structure for FDD is applicable to both full duplex and half duplex FDD. Each radio frame is 10ms long and consists of 20 slots of length 0.5ms, numbered from 0 to 19. A subframe is defined as two consecutive slots, as shown in Figure 3.20.

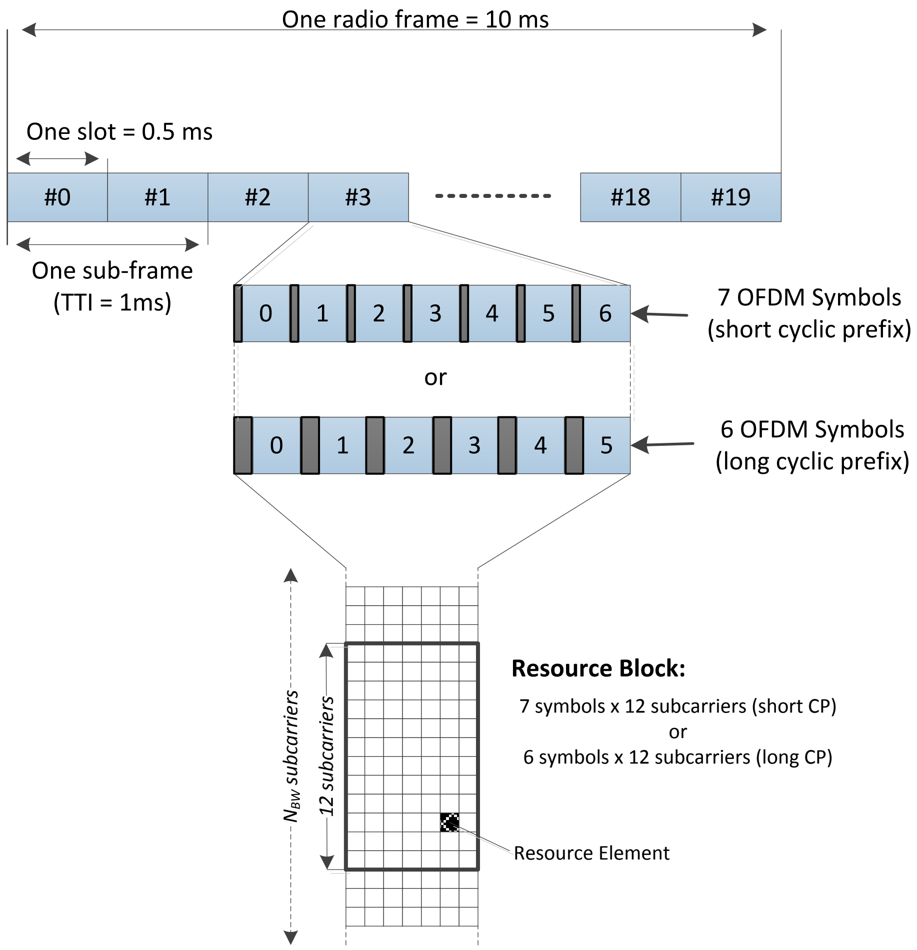

Figure 3.20: *Physical mapping of LTE-A*

For FDD, 10 subframes are available for downlink transmission and 10 subframes are available for uplink transmissions in each 10ms interval. Uplink and downlink transmissions are separated in the frequency domain. In half-duplex FDD operation, the UE cannot transmit and receive at the same time while there are no such restrictions in full-duplex FDD.

For LTE, In FDD applications, the uplink uses the same generic frame structure as the downlink. It also uses the same subcarrier spacing 15 kHz and 12 subcarriers width PRBs. Downlink modulation parameters including short and long CP length are identical to the uplink parameters shown in Table 3.6.

Table 3.6: *LTE-A physical resource parameters*

Access Scheme	DL	OFDMA
	UL	SC-FDMA
Bandwidth		1.4, 3, 5, 10, 15, 20 MHz
Minimum TTI		1ms
Cyclic prefix length	Short	4.7 us

	Long	16.7 us
Modulation		QPSK, 16QAM, 64QAM
Spatial multiplexing		Single layer for UL per UE Up to 4 layers for DL per UE MU-MIMO supported for UL and DL

Cyclic Prefix

It is a set of samples which are duplicated from the end of a transmitted symbol. This can form a type of guard interval to absorb Inter-Symbol Interference (ISI). The cyclic construction preserve orthogonality of the subcarriers in an OFDM transmission.

TDD in LTE

TDD in LTE is also possible. TDD spectrum is unpaired and assigned frequency bandwidth is used for uplink and downlink. A structure of TDD radio frame is illustrated in Figure 3.21, below.

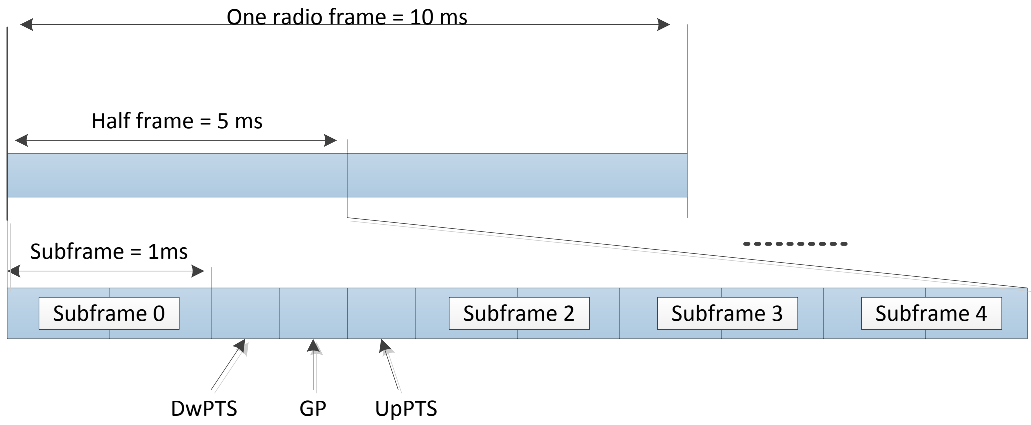

Figure 3.21: *LTE TDD radio frame structure*

In case of 5ms downlink-to-uplink switch-point periodicity, the special sub-frame exists in both half-frames. In case of 10ms downlink-to-uplink switch-point periodicity, the special sub-frame exists in the first half-frame only. Sub-frames 0 and 5 and DwPTS are always reserved for downlink transmission. UpPTS and the sub-frame immediately following the special sub-frame are always reserved for uplink transmission. GP is a Guard Period.

3.8 Transport Channels

From the physical layer, the MAC layer uses services in the form of Transport Channels. A transport channel is defined by how and with what characteristics the information is transmitted over the radio interface. Following the notation from HSPA, which has been inherited for LTE, data on a transport channel is organized into transport blocks. In each Transmission Time Interval (TTI), at most one transport block of a certain size is transmitted over the radio interface to/from a mobile terminal in absence of spatial multiplexing. In case of spatial multiplexing ("MIMO"), there can be up to two transport blocks per TTI.

3.8.1 HSPA+

- ***Dedicated Channel*** **(DCH)** is a downlink or uplink transport channel. The DCH is transmitted over the entire cell or over only a part of the cell using e.g. beam-forming antennas.
- ***Enhanced Dedicated Channel*** **(E-DCH)** is an uplink transport channel.
- ***Broadcast Channel*** **(BCH)** is a downlink transport channel that is used to broadcast system and cell-specific information. The BCH is always transmitted over the entire cell and has a single transport format.
- ***Paging Channel*** **(PCH)** is a downlink transport channel used for transmission of paging information from the PCCH logical channel. The PCH supports *discontinuous reception* (DRX) to allow the mobile terminal to save battery power by waking up to receive the PCH only at predefined time instants.
- ***Forward Access Channel*** **(FACH)** is a downlink transport channel. The FACH is transmitted over the entire cell. The FACH can be transmitted using power setting.
- ***High Speed Downlink Shared Channel*** **(HS-DSCH)** is a downlink transport channel shared by several UEs. The HS-DSCH can be associated with one downlink DPCH or F-DPCH, and one or several Shared Control Channels (HS-SCCH). The HS-DSCH is transmitted over the entire cell or over only part of the cell using e.g. beam-forming antennas.
- ***Random Access Channel*** **(RACH)** is an uplink transport channel. The RACH is always received from the entire cell. The RACH is characterized by a collision risk and by being transmitted using open loop power control.

3.8.2 LTE

- ***Broadcast Channel*** **(BCH)** has a fixed transport format, provided by the specifications. It is used for transmission of parts of the BCCH system information, more specifically the so-called *Master Information Block* (MIB).
- ***Paging Channel*** **(PCH)** is used for transmission of paging information from the PCCH logical channel. The PCH supports *discontinuous reception* (DRX) to allow the mobile terminal to save battery power by waking up to receive the PCH only at predefined time instants.
- ***Downlink Shared Channel*** **(DL-SCH)** is the main transport channel used for transmission of downlink data in LTE. It supports key LTE features such as dynamic rate adaptation and channel-dependent scheduling in the time and frequency domains, hybrid ARQ with soft combining, and spatial multiplexing. It also supports DRX to reduce mobile-terminal power consumption while still providing an always-on experience. The DL-SCH is also used for transmission of the parts of the BCCH system information not mapped to the BCH and for single-cell MBMS services.
- ***Multicast Channel*** **(MCH)** is used to support MBMS. It is characterized by a semi-static transport format and semi-static scheduling. In case of multi-cell transmission using MBSFN, the scheduling and transport format configuration is coordinated among the cells involved in the MBSFN transmission.
- ***Uplink Shared Channel*** **(UL-SCH)** is the uplink counterpart to the DL-SCH that is the uplink transport channel used for transmission of uplink data.
- ***Random Access Channel*** **(RACH)** is also defined as a transport channel although it does not carry transport blocks.

3.9 Physical Channels and Physical Signals

A physical channel corresponds to the set of time–frequency resources used for transmission of a particular transport channel and each transport channel is mapped to a corresponding physical channel as shown in Figures 3.22, 3.23 and 3.24. In addition to the physical channels with a corresponding transport channel, there are also physical channels without a corresponding transport channel. These channels, known as L1/L2 control channels, are used for downlink control information (DCI), providing the terminal with the necessary information for proper reception and decoding of the downlink data transmission, and uplink control information (UCI) used for providing the scheduler and the hybrid-ARQ protocol with information about the situation in the terminal.

3.9.1 HSPA+

- ***Dedicated Physical Data Channel*** **(DPDCH)** is used to carry the DCH transport channel. There may be zero, one, or several uplink DPDCHs on each radio link.
- ***Dedicated Physical Control Channel*** **(DPCCH)** is used to carry control information generated at Layer 1. The Layer 1 control information consists of known pilot bits to support channel estimation for coherent detection, transmit power-control (TPC) commands, feedback information (FBI), and an optional transport-format combination indicator (TFCI).
- ***Fractional Dedicated Physical Channel*** **(F-DPCH)** carries control information generated at layer 1 (TPC commands). It is a special case of downlink DPCCH. Each frame of length 10ms is split into 15 slots, each of length Tslot = 2560 chips, corresponding to one power-control period.
- ***E-DCH Dedicated Physical Data Channel*** **(E-DPDCH)** is used to carry the E-DCH transport channel. There may be zero, one, or several E-DPDCH on each radio link.
- ***E-DCH Dedicated Physical Control Channel*** **(E-DPCCH)** is a physical channel used to transmit control information associated with the E-DCH. There is at most one E-DPCCH on each radio link.
- ***E-DCH Absolute Grant Channel*** **(E-AGCH)** is a fixed rate (30 kbps, SF=256) downlink physical channel carrying the uplink E-DCH absolute grant. An E-DCH absolute grant shall be transmitted over one E-AGCH sub-frame or one E-AGCH frame. The transmission over one E-AGCH sub-frame and over one E-AGCH frame shall be used for UEs for which E-DCH TTI is set to respectively 2ms and 10ms.
- ***E-DCH Relative Grant Channel*** **(E-RGCH)** is a fixed rate (SF=128) dedicated downlink physical channel carrying the uplink E-DCH relative grants.
- ***E-DCH Hybrid ARQ Indicator Channel*** **(E-HICH)** is a fixed rate (SF=128) dedicated downlink physical channel carrying the uplink E-DCH hybrid ARQ acknowledgement indicator.
- ***Physical Random Access Channel*** **(PRACH)** is used to carry the RACH.
- ***Common Pilot Channel*** **(CPICH)** is a fixed rate (30 kbps, SF=256) downlink physical channel that carries a pre-defined bit sequence. In case transmit diversity is used on P-CCPCH and SCH, the CPICH shall be transmitted from both antennas using the same channelization and scrambling code. In this case, the pre-defined bit sequence of the CPICH is different for Antenna 1 and Antenna 2. In case of no transmit diversity, the bit sequence of Antenna 1 is used.
- ***Primary Common Control Physical Channel*** **(P-CCPCH)** is a fixed rate (30 kbps, SF=256) downlink physical channels used to carry the BCH transport channel.

- ***Secondary Common Control Physical Channel*** **(S-CCPCH)** is used to carry the FACH and PCH. There are two types of Secondary CCPCH: those that include TFCI and those that do not include TFCI.
- ***Synchronization Channel*** **(SCH)** is a downlink signal used for cell search. The SCH consists of two sub channels, the Primary and Secondary SCH. The 10ms radio frames of the Primary and Secondary SCH are divided into 15 slots, each of length 2560 chips.
- ***Acquisition Indicator Channel*** **(AICH)** is a fixed rate (SF=256) physical channel used to carry Acquisition Indicators (AI). Acquisition Indicator AIs corresponds to signatures on the PRACH.
- ***Paging Indicator Channel*** **(PICH)** is a fixed rate (SF=256) physical channel used to carry the paging indicators.
- ***MBMS Notification Indicator Channel*** **(MICH)** The MBMS Indicator Channel (MICH) is a fixed rate (SF=256) physical channel used to carry the MBMS notification indicators. The MICH is always associated with an S-CCPCH to which a FACH transport channel is mapped.
- ***High Speed Physical Downlink Shared Channel*** **(HS-PDSCH)** is used to carry the HS-DSCH. A HS-PDSCH corresponds to one channelization code of fixed spreading factor SF=16 from the set of channelization codes reserved for HS-DSCH transmission. An HS-PDSCH may use QPSK, 16QAM or 64QAM modulation symbols.
- ***HS-DSCH-related Shared Control Channel*** **(HS-SCCH)** is a fixed rate (60 kbps, SF=128) downlink physical channel used to carry downlink signalling related to HS-DSCH transmission.
- ***Dedicated Physical Control Channel (uplink) for HS-DSCH*** **(HS-DPCCH**) carries uplink feedback signalling related to downlink HS-DSCH transmission and to HS-SCCH orders. The feedback signalling consists of Hybrid-ARQ Acknowledgement (HARQ-ACK) and Channel-Quality Indication (CQI) and in case the UE is configured in MIMO mode of Pre-coding Control Indication (PCI) as well.

Mapping transport channels to/from physical channels:

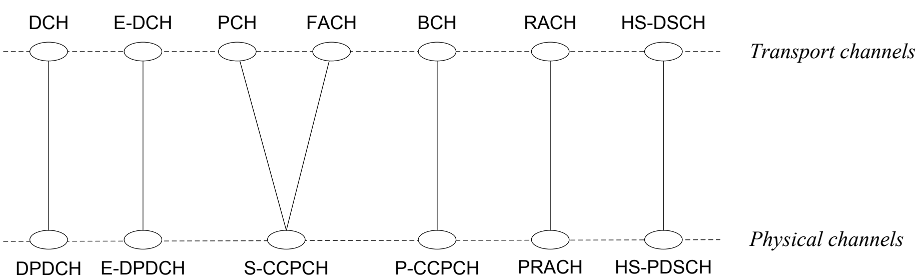

Figure 3.22: *HSPA+ channel mapping*

3.9.2 LTE

- ***Physical Downlink Shared Channel* (PDSCH)** is the main physical channel used for unicast transmission, but also for transmission of paging information.
- ***Physical Broadcast Channel* (PBCH)** caries part of the system information, required by the terminal in order to access the network.
- ***Physical Multicast Channel* (PMCH)** is used for MBSFN operation.
- ***Physical Downlink Control Channel* (PDCCH)** is used for downlink control information, mainly scheduling decisions, required for reception of PDSCH and for scheduling grants enabling transmission on the PUSCH.
- ***Physical Hybrid-ARQ Indicator Channel* (PHICH)** carries the hybrid-ARQ acknowledgement to indicate to the terminal whether a transport block should be retransmitted or not.
- ***Physical Control Format Indicator Channel* (PCFICH)** is a channel providing the terminals with information necessary to decode the set of PDCCHs. There is only one PCFICH in each cell.
- ***Physical Uplink Shared Channel* (PUSCH)** is the uplink counterpart to the PDSCH. There is at most one PUSCH per terminal.
- ***Physical Uplink Control Channel* (PUCCH)** is used by the terminal to send hybrid-ARQ acknowledgements, indicating to the eNodeB whether the downlink transport block(s) was successfully received or not, to send channel-status reports aiding downlink channel-dependent scheduling, and for requesting resources to transmit uplink data upon. There is at most one PUCCH per terminal.
- ***Physical Random Access Channel* (PRACH)** is used for random access in uplink direction.

Mapping transport channels to/from physical channels:

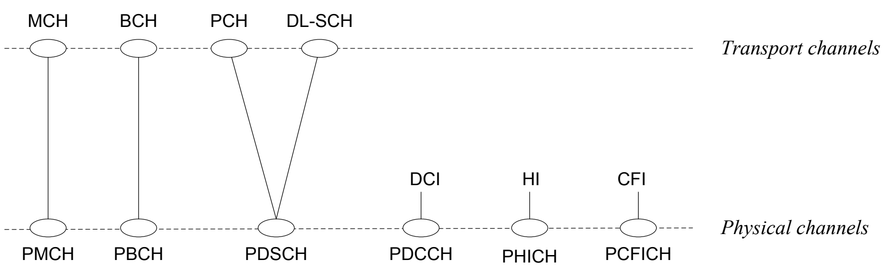

Figure 3.23: *LTE downlink channel mapping*

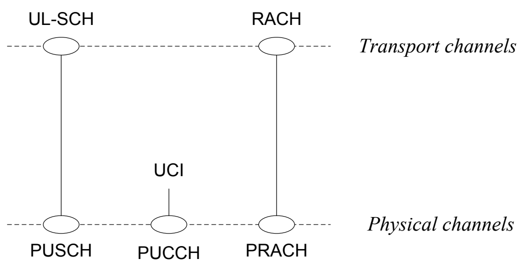

Figure 3.24: *LTE uplink channel mapping*

3.10 **Conclusion**

The comparison of physical layers of HSPA+ release 7 and LTE-Advanced release 10 has shown main differences between these technologies. Although the first few steps after initialisation of transport block are the same, channel codes are quite different and complex turbo coding is used for more channels in LTE-A. On the other hand, rate matching is more universal in this case and whole structure of LTE-Advanced is simpler.

Main differences are obvious in the part of physical channel processing. In HSPA+, TrCHs are merged onto CCTrCH and then segmented to each stream. For LTE-A, each TrCH is modulated and mapped to outline layers. MIMO precoding is implemented in this process and resource mapper only place symbols to the resource matrix. Each MIMO stream has its own resource mapper and output signal modulator.

Antenna mapping in HSPA+ is either simple stream or MIMO stream. A 10ms radio frame contains 5 sub-frames equal to TTI length which are directly modulated to the carrier and spread to UE side. In case of MIMO, two streams combine each other and then they are spread in the same time. In LTE-A, there is also a radio frame length of 10ms although it is divided onto 20 slots which are modulated to its own subcarrier. A matrix 7 x 12 subcarriers creates a resource block. The resource block is the smallest unit that can be scheduled to the user. Each resource block is then spread by OFDM or SC-FDMA. LTE is also able to use MIMO processed before spreading.

Transport and physical channels are listed in sections 3.8 and 3.9, also with mapping schemas. HSPA+ uses much more channels, specified for each signalling and user data carrying. Since LTE-A uses different methods of transmission for UL and DL, these channels are relatively reduced.

Compare to HSPA+, LTE-Advanced has its strength in the ability of process more TrCH in one TTI. It is also more flexible with modulation and spreading and additional features such a carrier aggregation or higher spatial multiplexing.

4 Deployment of LTE/SAE in the World

4.1 Preface

Deployment of mobile networks has risen mainly because of higher capacity demands related to increasing number of mobile devices. Development progress is not only to create a new network with higher capabilities. It also has to provide a backward compatibility with current network technologies.

In the world, there are authorized institutes responsible, among others, for mapping of telecommunication networks integration and deployment. Some of them are The Global mobile Suppliers Association (GSA), GSM Association (GSMA), World Cellular Information Service (WCIS+) and others.

4.2 Current State

Nowadays, there is currently 162 LTE networks in the world, providing its services in commercial sphere. Countries given this mobile broadband technology reach number 68.

It is important to notice, the LTE networks coverage is mostly situated in cities, big towns and areas with larger number of subscribers. Many networks are in the pilot version restricted to a small areas or towns.

4.2.1 Americas

In North and Latin America, there is currently 44 networks in service. More than 50% of them work in frequency bands around 700 MHz and 2.1 GHz using FDD, as shown in Figure 4.1, below. There are also two providers using natively American network AWS (around 1700MHz uplink / 2100MHz downlink). Over 25 of this providers is operating in North America, where in US is covered around 62% of population. Yet, this networks are primarily used for Internet access. However, there is already one provider offering Voice over LTE (VoLTE) in US. List of all American operators providing LTE is the subject of Attachment.A.

- **11 countries**
- 44 providers (One provider with VoLTE.)

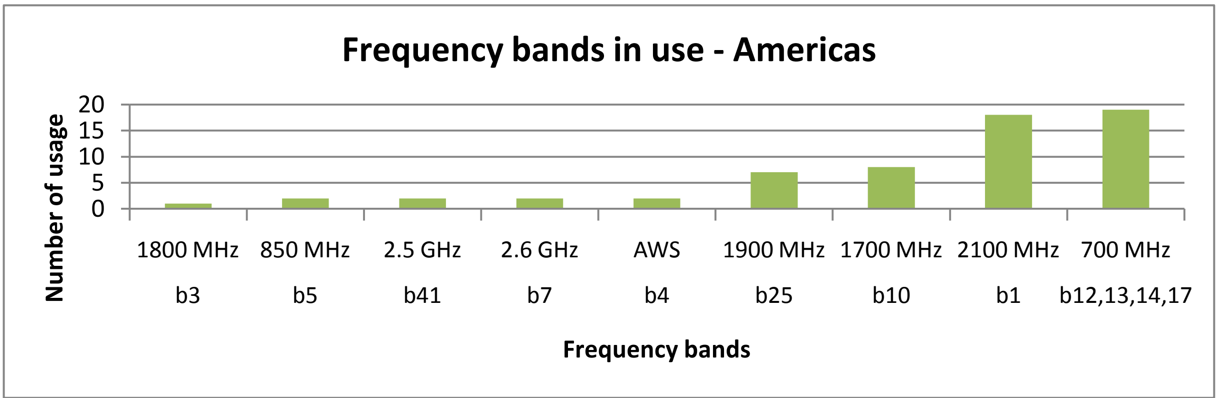

Figure 4.1: *LTE frequency bands - Americas*

4.2.2 Asia Pacific and Oceania

Including Australia and New Zealand, there are completely 28 providers responsible for covering this area by LTE signal, as shown in Attachment.B. One of the most expanded marketplace is Japan and South Korea where all providers offer LTE services. Moreover there are two out of three networks in South Korea provide VoLTE, since August 2012. About the frequency spectrum usage, the most employed bands are the Band VII and the Band III working around 2.6 GHz and 1800 MHz. Comparison of these bands is shown in Figure 4.2.

- **11 countries**
- 28 providers (Two providers with VoLTE.)

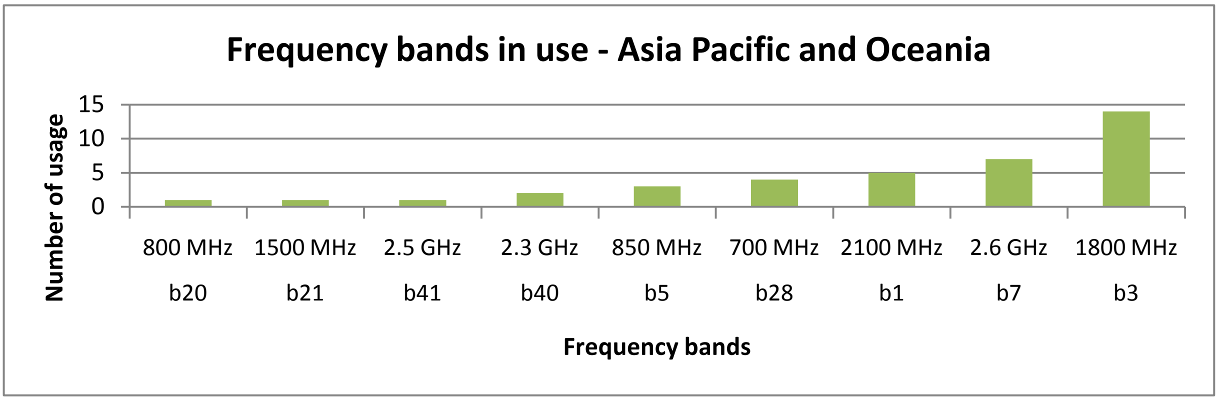

Figure 4.2: *LTE frequency bands – Asia Pacific and Oceania*

4.2.3 Europe

For the European Union and neighbouring states there has been counted 29 countries with completely 63 providers of LTE. As the most perspective frequency bands has been chosen Band XX, Band III/IX and Band VII, illustrated in Figure 4.3. Special case is a frequency around 3.5 GHz associated to Band XLII. This band belongs to nonstandard and it has been using in UK as TDD. List of European LTE providers is available in Attachment.C.

- **29 countries**
- 63 providers

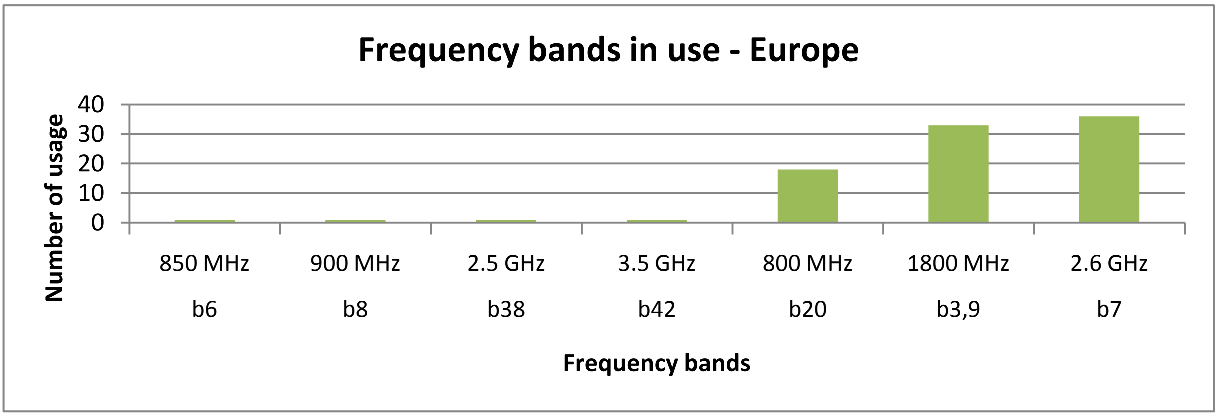

Figure 4.3: *LTE frequency bands – Europe*

4.2.4 Middle East and Africa

Frequency bands used for LTE in Africa are similar as in Europe. In Figure 4.4 below there is an evident that two most used are 1800 MHz and 2600 MHz. Anyway, the frequency band 2100 MHz is also getting employed. However, this part of the world has still a lot of differences in living standard which is reflected to coverage, situated only in densely populated areas. In Attachment.D are shown current LTE networks in commercial service.

- **17 countries**
- 27 providers

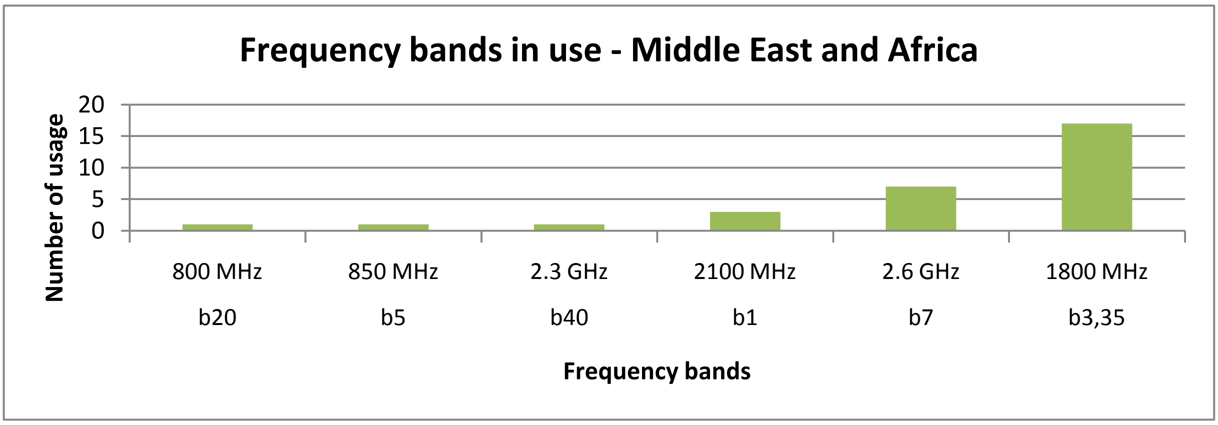

Figure 4.4: *LTE frequency bands – Middle East and Africa*

4.3 Future development

Currently, there are 162 LTE networks in a commercial service in the world. Additional 278 networks are in Trial, planned or in deployment. There are other 246 new commercial LTE networks expected until the end of year 2013.

Nowadays, number of users is increasing very quickly. At the end of year 2012, the number of subscribers reached 63 millions. For the next year it is supposed to reach 134 millions subscribers. Forecast in Figure 4.5, below, shows likely increase in following years.

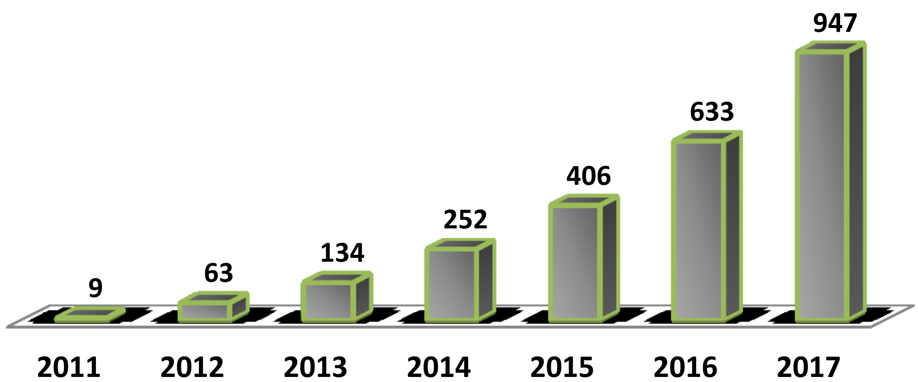

Figure 4.5: *Forecast of subscribers [27]*

4.4 Conclusion

The LTE networks are very perspective. Supporting all services previously provided by 2G and 3G networks they achieve great response from customers.

The most common LTE band 1800 MHz is used in over 45% of commercially launched networks. Second widely used band is 2600 MHz. These bands belong to commonly higher LTE bands. By their propositions they are mostly utilized for covering of densely populated areas. On the other hand, band 900MHz is not used for LTE because it was widely used for deployment of GSM which is still the most common mobile communication network in the world.

The highest deployment is in Europe and America where more than 100 MNOs completely operate nowadays. Although there are many so-called virtual operators using networks of real MNOs. In Asia, especially South Korea there has been launched first LTE-Advanced network in the world, in June 2013. Integration of Carrier Aggregation has been planned to 2015. Japan and main cities in China also belong to world most advanced areas in this field.

As noticed, forecast of subscribers has been made by statistics of present deployment, so it may contain irregularities.

5 Analysis of LTE/SAE deployment in the Czech Republic

5.1 Preface

Since 2007, there are four telecommunication carriers in the Czech Republic providing mobile network services in a public sector. While the newest one U:fon managed by Air Telecom a.s. works in bands 410 MHz to 430 MHz and uses CDMA technology, the rest of them works in a globally standardized bands and technologies such a GSM, UMTS or HSPA. These three providers are Telefonica O2 belonging to Telefonica Czech Republic a.s., T-Mobile managed by T-Mobile Czech Republic a.s. and Vodafone Czech Republic a.s..

Nowadays, the situation in a telecommunication market in the Czech Republic is going to meet huge changes because of forthcoming auction of a Digital Dividend. The subject of this auction consists of three categories of blocks in band 800 MHz, two categories of blocks in 1800 MHz and two categories of blocks in band 2600MHz. This blocks are primarily intended for application of high-speed data transmission networks, such an LTE.

From the perspective of backbone networks, as far as the auction is focused on the improvement of telecommunication networks up to 4G, changes had to take effect by increasing of their capacity.

In terms of legislation, a Czech Telecommunication Office (ČTÚ) specifies the exact dates and performance to be achieved by using of the auction frequencies.

5.2 Current state of deployment

5.2.1 Telefonica O2

Telefonica O2 Czech Republic commercially launched LTE-1800 service in Jesenice, Prague in June 2012 using 2x10MHz. It is serving around 10 000 people with a maximum data rate of 60Mbps. In May 15, the LTE network was expanded to districts Prague 1, Prague 2, Prague 4 and Prague 10. The coverage of Telefonica's LTE is shown in Figure 5.1.

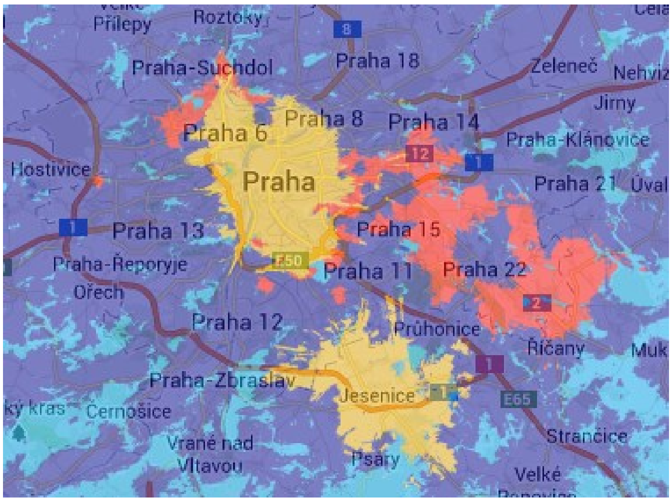

Figure 5.1: *Coverage by LTE of Telefonica (the yellow areas)*

Access to this network is allowed only for special SIM cards distributed in this areas. An LTE cannot be use simultaneously with voice services on one SIM card, yet.

In addition, Telefonica O2 provides UMTS in more than 30% of Czech territory (75% of population) with maximum transmission data peak rate of 2,2Mbps. It also provides EDGE services.

5.2.2 T-Mobile

T-Mobile Czech Republic announced inauguration in July 2012 of an LTE trial in Prague's Kamyk district with 12 base stations using 20MHz of 2.6 GHz spectrum. As a testing network, the operation was planned to end in September 2012. In November 2012 the network was extended to the city of Mlada Boleslav using 19 transmitters in 2x10 MHz of 1800 MHz spectrum (LTE-1800). This network was considered as a pilot, available only to customers with special SIM card edition. On 1st July, T-Mobile has launched a next LTE network in Prague 4 and allowed LTE services to all customers for free. Nowadays, T-Mobile use only frequency band LTE-1800 with allocated bandwidth 10 or 15MHz. A maximum data rate provided by T-Mobile is up to 100Mbps for DL and up to 37,5Mbps for UL. The coverage of LTE is pictured in Figure 5.2.

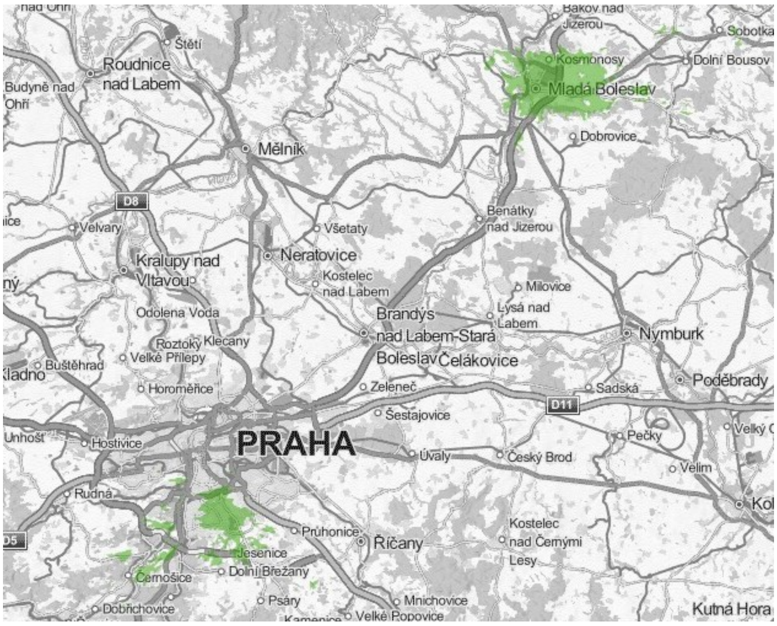

Figure 5.2: *LTE coverage of T-Mobile*

A voice services are, in this case, provided by CS Fall Back (CSFB) which transforms call to 3G or 2G network. A VoLTE is not allowed.

T-Mobile also provides DC-HSPA+/HSPA+ for more than 85% of population and EDGE packet network for approximately 99% of population.

5.2.3 Vodafone

Vodafone has launched its first LTE network in June 2013 in Karlovy Vary. The LTE-1800 baseband has been used by bandwidths 2x10MHz and 2x15MHz in 20 eNodeB base stations. A maximum data rate reach 100Mbps for DL. The technology vendor is Huawei and a voice services are also provided by CS Fall Back. Map of current LTE coverage is in Figure 5.3.

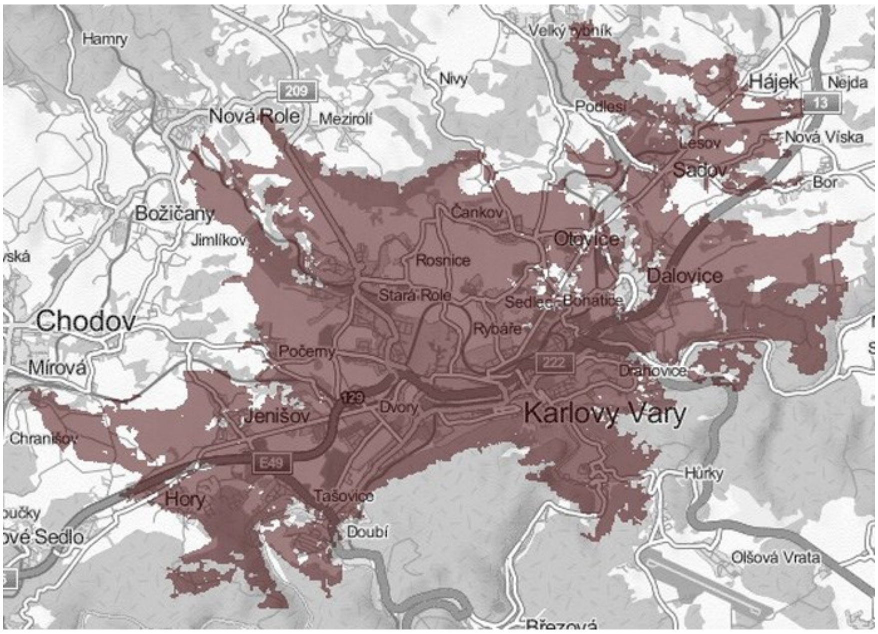

Figure 5.3: *LTE coverage of Vodafone*

Vodafone Czech Republic is currently running DC-HSPA+ with peak data rate of 43,2 Mbps as network with the fastest data transmission. In addition, it also allows GPRS and EDGE on 98% of Czech territory and HSPA+ Release 7 available for more than 73% of population.

In 2012, Vodafone expanded its fibre network from 1500km to more than 6000km due to preparation for the coming of LTE.

5.2.4 Air Telecom

U:fon uses CDMA EVDO rev. A with theoretical peak data rate of 3,1Mbps covering more than 75% of Czech Republic. As a trademark it does not continue even to GSM broadband. Anyway, Air Telecom a.s. is starting to use GSM bands nowadays. After all, moving on to LTE has not been considered yet.

5.3 Auction of Digital Dividend

On April 8, 2013, regulator CTU issued terms and conditions for a second auction of 800, 1800 and 2600MHz. Among other, new rules allocates 2x10Mhz on 800MHz band (Cat. A3) only for new providers giving an advantage to PPF Mobile Services. This band is the most perspective and crucial for covering huge areas with minimal cost.

The way how effectively use frequency plan is the same as in previous generations. Low frequencies of around 800MHz and 900MHz will be used, if it is possible, for covering large areas (macro cells) and country side. It is characterized by large signal range with relatively low power consumption. Cities are usually covered by higher frequencies.

Frequency planning of LTE networks is not a big deal for "big three" Czech providers. All of them have already enough frequencies to build another network. Although, success in forthcoming auction can change a way of their effective use.

5.3.1 Auction subjects [19]

Auction is separated onto seven categories which belong to different rules and different starting price. The categories A2, B2, C and D are listed as abstract. It means that is does not matter on the obtained block ID. Table 5.1 introduces a categories A.

Table 5.1: *Paired band 800MHz*

Cat.	ID	Downlink	Uplink	Bandwidth in MHz
A1	A1.1	791 - 796	832 - 837	2 x 5
A2	A2.1	796 - 801	837 - 842	2 x 5
	A2.2	801 - 806	842 - 847	2 x 5
	A2.3	806 - 811	847 - 852	2 x 5
A3	A3.1	811 - 821	852 - 862	2 x 10

A total volume of bandwidth per applicant must not exceed 2 x 22,5MHz, as a sum of all held frequencies in 900MHz and 800MHz, which is the subject of this auction. Also a total volume of bandwidth obtained in this auction must not exceed 2x10MHz per applicant in band 800MHz. As noted, block A3 is reserved only for new potential providers (Only for applicants which have not held frequencies in band 900MHz).

A blocks of category "B" are situated in band 1800MHz. It is also a paired band which means that each block has an equivalent part predetermined for downlink and uplink. List of these blocks is shown in Table 5.2.

Table 5.2: *Paired band 1800MHz*

Cat.	ID	Downlink	Uplink	Bandwidth in MHz
B1	B1.1	1805,1 - 1805,3 1842,3 - 1857,9	1710,1 - 1710,3 1747,3 - 1762,9	2 x 15,8
B2	B2.1	1805,3 - 1806,3	1710,3 - 1711,3	2 x 1
	B2.2	1816,9 - 1817,9	1721,9 - 1722,9	2 x 1
	B2.3	1817,9 - 1818,9	1722,9 - 1723,9	2 x 1

	B2.4	1822,3 - 1823,3	1727,3 - 1728,3	2 x 1
	B2.5	1823,3 - 1824,3	1728,3 - 1729,3	2 x 1
	B2.6	1875,9 - 1876,9	1780,9 - 1781,9	2 x 1
	B2.7	1876,9 - 1877,9	1781,9 - 1782,9	2 x 1
	B2.8	1877,9 - 1878,9	1782,9 - 1783,9	2 x 1
	B2.9	1878,9 - 1879,9	1783,9 - 1784,9	2 x 1

A rule assigned by CTU for category "B" is that a total volume of bandwidth per applicant must not exceed 2 x 23MHz as a sum of held frequency bands in 1800MHz and bands in 1800MHz belong to this auction.

A category "C" contains completely 14 paired blocks of bandwidth 2x5MHz. The category is in the range 2600MHz which is not so usable for covering of huge areas such a macro cells. Table 5.3 contains a list of blocks in this category.

Table 5.3: *Paired band 2600MHz*

Cat.	ID	Downlink	Uplink	Bandwidth in MHz
C	C1	2620 - 2625	2500 - 2505	2 x 5
	C2	2625 - 2630	2505 - 2510	2 x 5
	C3	2630 - 2635	2510 - 2515	2 x 5
	C4	2635 - 2640	2515 - 2520	2 x 5
	C5	2640 - 2645	2520 - 2525	2 x 5
	C6	2645 - 2650	2525 - 2530	2 x 5
	C7	2650 - 2655	2530 - 2535	2 x 5
	C8	2655 - 2660	2535 - 2540	2 x 5
	C9	2660 - 2665	2540 - 2545	2 x 5
	C10	2665 - 2670	2545 - 2550	2 x 5
	C11	2670 - 2675	2550 - 2555	2 x 5
	C12	2675 - 2680	2555 - 2560	2 x 5
	C13	2680 - 2685	2560 - 2565	2 x 5
	C14	2685 - 2690	2565 - 2570	2 x 5

For those interested in category "C", a total volume of bandwidth obtained per applicant must not exceed 2 x 20MHz in paired band of 2600MHz.

The last category is also in band 2600MHz, although it is an unpaired part. It contains 10 blocks of 5MHz bandwidth. List of blocks in category "D" is a content of Table 5.4.

Table 5.4: *Unpaired band 2600MHz*

Cat.	ID	Unpaired frequency range	Bandwidth in MHz
D	D1	2570 - 2575	5
	D2	2575 - 2580	5
	D3	2580 - 2585	5

	D4	2585 - 2590	5
	D5	2590 - 2595	5
	D6	2595 - 2600	5
	D7	2600 - 2605	5
	D8	2605 - 2610	5
	D9	2610 - 2615	5
	D10	2615 - 2620	5

The limit for an unpaired band 2600MHz is not set, although CTU has dictate a rule says that the block D10 will be assign to holder of block D9. It has been considered as a way how effectively use this block due to the potential interference.

5.4 Legislation terms [19]

5.4.1 Terms of usage of frequencies in band 800MHz

The public telecommunication network operates in band 800MHz have to fulfil a conditions of European standard 2010/267/EU [20] about a technical parameters and also a conditions of norms ETSI, CEPT or ITU [21] depends on the chosen standard. A terms of use have been defined for 800MHz band as follows:

- An FDD duplex usage with a duplex separation of 41MHz. For a base stations transmission is used a lower frequency.
- A limit value of Equivalent Isotropically Radiated Power (EIRP) on base station is +60 dBm/(5 MHz) or lower, depends to interference
- A limit values of radiation inside of block are declared in Table 5.5.

Table 5.5: *Limit values of radiation for band 800MHz* [19]

Frequency radiation ranges inside of block	Maximum mean value of EIRP inside of block
Protection band between the edge of radio broadcasting band in 790MHz and the edge of FDD communication band for downlink **(790-791 MHz)**	+17,4 dBm/MHz
Frequencies used for FDD downlink **(791-821 MHz)**	+22 dBm/(5 MHz) in range -5 to 0 MHz from the lower edge of block, and in range0 to +5 MHz from the upper edge of block +18 dBm/(5 MHz) in range -10 to -5 MHz from the lower edge of block, and in range +5 to +10 MHz from the upper edge of block +11 dBm/(MHz) for the rest of frequencies used for downlink
Protection band between the edge of FDD downlink band and the edge of FDD uplink band	+15 dBm/MHz

(821-832 MHz)	
Frequencies used for FDD uplink **(832-862 MHz)**	-49,5 dBm/(5 MHz)

- A radiation limits EIRP inside of blocks for Block Edge Mask (BEM) of base stations use frequencies lower than 790MHz are dictated by Table 5.6.

Table 5.6: *Limit values of EIRP for frequencies lower than 790MHz* [19]

Terms of EIRP value inside of block for base stations, P [dBm/10MHz]	**Maximum mean value of EIRP inside of block**
$P \geq 59$	0 dBm/(8 MHz)
$36 \leq P \leq 59$	(P-59) dBm/(8 MHz)
$P < 36$	-23 dBm/(8 MHz)

- A radiation limit value BEM inside of block for UE uses FDD uplink must be +23dBm. A deflection of +2dBm is also tolerated.

Holders of frequency blocks in band 800MHz are also required to cover 95% of Czech population by minimum 2Mbps downlink data rate within 7 years. In order to ensure even coverage, Czech Republic was notionally split onto two kinds of districts. Districts “A”, Attachment.E, with lower population and districts “B”, Attachment.F, with higher population. If the participant obtains more than 2x5MHz frequency band unit, it has to cover systematically firstly one district in group “A” to launch operation in one district in group “B”. To operate in the rest of districts in group “B”, all the districts “A” must be covered.

By coverage, it is meant an operation of public communications network in bands 800MHz, 1800MHz or 2600MHz, which is able to provide high speed internet connection for at least 95% of population in the district with 75% probability of indoor reception.

5.4.2 Terms of usage of frequencies in band 1800MHz

The public telecommunication network operates in band 1800MHz have to also fulfil a technical parameters and conditions of norms ETSI, CEPT or ITU [21]. They also have to operate in accordance with the European standard 2011/251/EU [22] and recommendation ERC REC (08)02 [23]. A terms of use have been defined for 1800MHz band as follows:

- Base stations operate in frequency band 1805-1880 / 1710-1785MHz must work in duplex mode with a duplex separation of 95MHz. For a base station transmission, the higher frequency is used.
- In terms of legislation, there are a specific demands for coexistence of GSM systems and systems from IMT group standards, especially IMT-2000/UMTS and LTE. The coexistence of these systems in band 1800MHz is possible due to following technical parameters in Table 5.7.

Table 5.7: *Demands of LTE coexistence [19]*

System	**Technical Parameters**
LTE in accordance with the standards of LTE issued by ETSI, in particular EN 301908-1, EN 301908-13, EN 301908-14 and EN 301908-11 [21]	1. Frequency spacing between the edge of LTE channel and the edge of GSM carrier frequency channel must be at least 200 kHz. This condition applies only between neighbouring networks LTE and GSM. 2. Frequency spacing between the edge of LTE channel and the edge of UMTS carrier frequency channel is not required. 3. Frequency spacing between the edges of LTE channels of two neighbouring LTE networks is not required.

For holders of bands in 1800MHz are the conditions bounded only to block B1. They dictate to cover at least 50% of Czech population by signal with minimum downlink data rate 2Mbps within 8 years by using 1800MHz or 2600MHz frequency band. After that, the minimum downlink rate must reach 5Mbps.

Services on the other frequencies in band 1800MHz are not limited.

5.4.3 Terms of usage of frequencies in band 2600MHz

Operation of networks in band 2600MHz has to be in accordance with technical specification 2008/477/ES [24] and a recommendation ERC REC (11)05 [25]. It also has to be in accordance with ETSI norms, CEPT or ITU [21], depends on provided services. A terms of use have been defined for 2600MHz band as follows:

- Base stations operate in frequency band 2620-2690 / 2500-2570MHz must work in duplex mode with a duplex separation of 120MHz. For a base station transmission, the higher frequency is used. A base stations in band 2570-2620MHz operate in simplex mode.

- A limit value of EIRP on base station is +61dBm/(5 MHz) inside of block, although there is an exception:
    - For a block D1 (2570-2575MHz), the limit value of EIRP is set to +25dBm/(5 MHz). The same value will be applied to each start-block of category D if there is more holders having their frequency blocks adjacent to each other. This restriction will not be applied for the block D1 if holder of blocks D1 and C10 is the same. Sense of this restriction is illustrated in Figure 5.4.

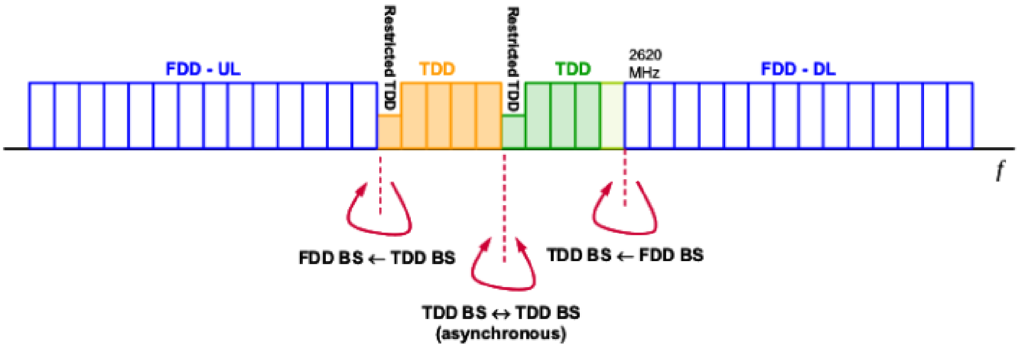

Figure 5.4: *EIRP restrictions for the frequency blocks cat. D*

Holders of frequencies in band 2600MHz are obliged to cover at least 30% of population by using this band within 7 years. The minimum rate is also 2Mbps for downlink. After that, it is necessary to provide a downlink data rate at least 5Mbps on end-user device.

In case, the holder of frequency block in band 2600MHz does not hold any frequency block in band 900MHz, the deadlines are extended for 12 months.

5.5 Backbone Networks

Incoming deployment of LTE networks in Czech Republic brings, among others, a massive changes for Mobile Network Operator's (MNO's) backbone networks. Since MNOs almost skipped the evolution steps of covering by newer HSPA+ technology, changes will be even greater.

5.5.1 Capacity issue

An LTE backbone networks require high throughput, low latency and IP protocol support since LTE networks are full-IP based. The best way how to achieve this requirements is to use an optical fibre network. Although, in certain cases the fibre connection is not possible due to cant or other obstruction. This connections can be established by microwave.

For a determination of backbone network demands it is necessary to know a theoretical capabilities of the system. In 3GPP specification 36.213 [26], table 7.1.7.1-1 shows the mapping between Modulation and Code Scheme (MCS) index and Transport Block Size (TBS) index. The highest MCS having reserved a TBS is the MCS index 28 with the TBS index 26. It is corresponding to TBS of 75376. Assume 2x2 MIMO, the downlink peak data rate given by table 7.1.7.2.2-1 is 149,8Mbps. By using 4x4 MIMO, the peak data rate is doubled (298Mbps).

In uplink side, the highest order modulation 64QAM with no MIMO corresponds to TBS, which is 75,4Mbps. Summary of these data rates is shown in Table 5.8.

Table 5.8: *Theoretical throughput of LTE (64QAM and 4x4MIMO)*

Channel Bandwidth	**Data rates [Mbps] according to used bandwidth**		
	Downlink	Uplink	Total
10MHz	150 (147,5)	37 (36,7)	187
15MHz	220 (220,3)	55 (55,1)	275
20MHz	300 (298)	75 (75,4)	375

In Czech Republic, there are actually used a bandwidths 2x10MHz and 2x15MHz. Although, the result of the auction of digital dividend could allow MNOs to use even 20MHz bandwidth, especially in band 1800MHz.

As the theoretical peak rate for LTE site is 375Mbps, it can never be achieved. For this reason, a fibre links established to a cell site have rate only about 100-200Mbps.

The MNOs operating in Czech Republic have more or less 5000 cell sites each. Many of them are shared and it is not excluded, MNOs will cooperate to rebuild these links.

5.5.2 Network topology

A structure of backbone network has a main impact to data distribution between cells and core network. Since LTE cells need to be connected also to its neighbour sites (X2 connection), the hierarchy of backbone network must be even complex. Price is also crucial factor for deployment of each connection. In Table 5.10 are pictured the main requirements for backbone networks. It is also obvious what topology meet these requirements at most.

Table 5.10: *Backbone network requirements*

Feature	Daisy chain	Hub and Spoke	Tree/ Tiered	Mesh/ Ring
Capacity distribution	⊘	✓	✓ ✓	✓ ✓ ✓
Achieve required network availability	⊘	✓ ✓	✓ ✓	✓ ✓ ✓
Provide LTE cell-to-cell connectivity (X2)	⊘ ⊘	✓	✓ ✓	✓ ✓ ✓
Network cost factor	✓	✓	✓	✓ ✓
Future proof factor	⊘	✓ ✓	✓ ✓	✓ ✓ ✓

The most perspective topology seems to be a mesh/ring structure. It features a recovery from any single link failure, high capacity and cell-to-cell connectivity. It is also easy to upgrade in case of future changes. A proper planning eases a ring capacity demands as shown in Figure 5.5. A multiple site packet capacity is not simply sum of cell capacities. By this way it is not necessary to establish a 100Mbps Ethernet link each cell site. Dataflow is effectively routed to less loaded lines.

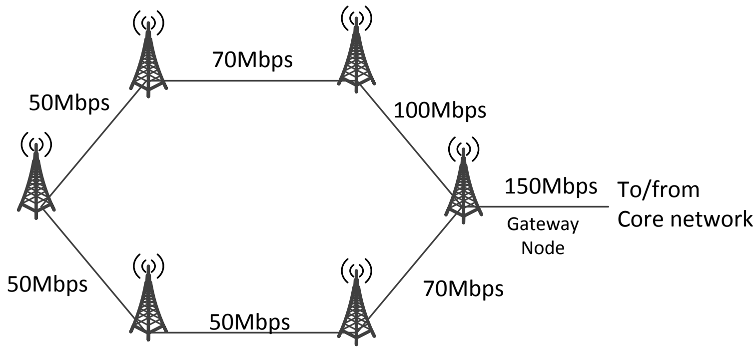

Figure 5.5: *Ring architecture example*

In this case, additional ring sites only add incremental capacity. An example of structure of whole backbone network illustrates Figure 5.6. Every connection of the network must be doubled in case of failure. All the core and aggregation part is built on optical fibre links, but there can be an exceptions.

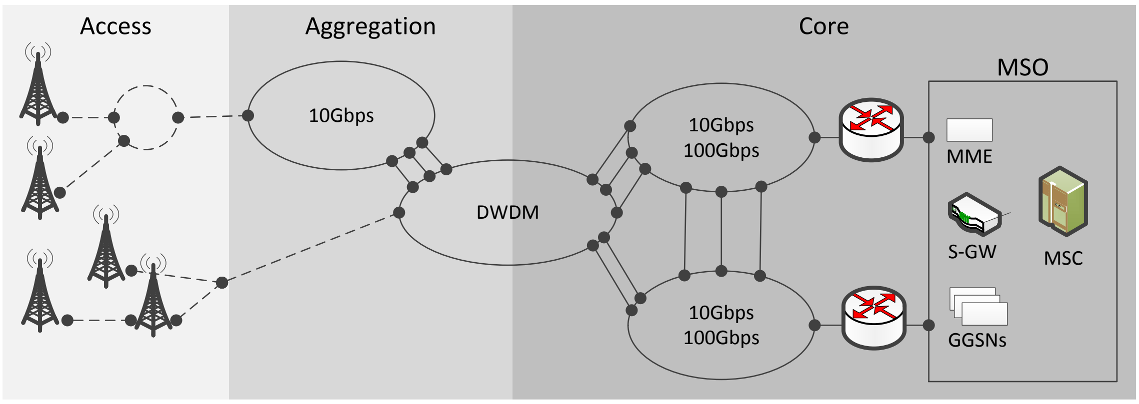

Figure 5.6: *Example of backbone network architecture*

As has been said, the access part uses fibre links or microwaves, depends to accessibility of each site. Relays are mostly mediated by microwaves.

5.5.3 Current State

According to unofficial sources, T-Mobile Czech Republic picked Cisco Systems routers as a future core of its LTE network as well as managing mobile traffic on its existing 2G and 3G infrastructure. As noticed, the contract for technology deployment belongs to Huawei. In terms of software-based solutions, Mavenir Systems has been chosen to provide converged IMS core and application servers, supporting services across wireless, wire line and enterprise. Construction is expected to begin later this year.

Telefonica O2 picked also Huawei as a supplier of LTE network technology with plans to expand their network this year. Over all, details have not been published yet. Of course, Telefonica still works on exchange and implementation of optical fibre network.

Vodafone extended its fibre network by more than 4500km last year. Later this year, they plan to establish more than 70 new intercity connections, along with connection to Vodafone international data network.

5.6 Future Development

Telefonica O2 plans to expand their LTE network to other parts of Prague (Prague1-7, Prague 10 and part of Prague 8) including Vaclav Havel International Airport in summer 2013. The city centre and the airport suppose to be covered until August. Telefonica also plans to launch their LTE network in a centre of Brno in October 2013.

T-Mobile has announced to continue with expanding of its LTE network in Prague at least until the end of 2013. It also depends on the result of the auction. The LTE network will operate in trial mode until September 2013. Partnership with its technology vendor Huawei still continues.

Beside Karlovy Vary, Vodafone has only announced to start with a commercial service until the end of summer 2013.

5.7 Conclusion

Nowadays, coverage of LTE in the Czech Republic is very poor and insufficient. Forthcoming auction of digital dividend offers much to change mobile network market in the Czech Republic. Beside the frequency blocks it also dictates conditions how to continue with building of LTE. This conditions have some changes and advantages for new potential MNOs to fulfil a purpose of this auction. The blocks offered only to new providers open the way for candidates such PPF Mobile Service which has participated, as only one new candidate, in last unsuccessful round of this auction.

This auction should start at the end of July. Bidding is expected in October. Blocks of category A are the most perspective which is reflected to starting price. From another point of view the last blocks of category D suppose to be partially noisy, so the starting price is quite reduced.

In terms of legislative, LTE networks must meet some conditions for smooth working and fulfilling the auction conditions, but none of them are unfeasible. All the bands must be compatible with European standards, which contain, among others, a radiation limit values, duplex separation in case of FDD and conditions for coexistence with other networks.

Backbone networks meet also huge changes due to LTE deployment. Providing and guaranteeing of LTE services, optical fibre or high capacity microwave link must be established to each eNodeB. Nowadays, MNOs establish this links with capacity up to 200Mbps. In combination with ring topology, it offers a sophisticated way how to evenly distribute load to the network.

6 Conclusion

Since year 2000, mobile networks have taken a long way. The evolution step is obvious in our daily life and the networks, firstly developed for voice services and access to Internet, are now a part of it. At the beginning, GSM networks designed to provide voice services have not fulfilled a needs of customers so they have given rise to UMTS networks, supporting voice and data services. As the number of customers has risen, new features and higher modulation had to be used to increase capacity and data rate. HSPA as a successor of UMTS took a place in mobile network sphere.

Enhancements of this technology brought HSPA+ in 2006 with data rate up to 28Mbps for downlink. Potential of 5 MHz bandwidth has been utilized maximally. Another releases of this technology mainly multiple carriers by using of higher bandwidth and extended spatial multiplexing to achieve higher data rate.

In 2008, LTE network has been released beside to Evolved Packet Core. The System Architecture Evolution, as it is dubbed by, changed and simplified network structure. Variable bandwidth and adaptive modulation are optimized to customer and network needs and take affect to actual data rate. LTE-Advanced success LTE and fulfil IMT-Advanced requirements for 4G networks. Due low latency and data rate up to 1Gbps, it opens way for future innovations.

Physical layer comparison of HSPA+ release 7 and LTE-Advanced release 10, as a two ground breaking technologies, has shown the way they succeed. Although HSPA+ is fixed to 5MHz bandwidth, it has been possible to provide downlink data rate up to 28Mbps. On the other hand, LTE-Advanced as a futuristic network allows to proceed more transport blocks in one 1ms TTI which is four times more than in HSPA+. Different spreading parameters, adaptive modulation and features such a Carrier Aggregation, 8x8MIMO or a Lean Carrier, allows to provide high data rate and effective utilization of frequency band. The spectral efficiency of LTE-Advanced release 10 is 30bps/Hz which is more than triple of HSPA+.

Since LTE networks bring all the advantages, they have been widely deployed around the world. Nowadays, there are more than 162 LTE networks in a commercial use and other 246 are expected until the end of 2013. As the most progressive markets are America and Europe, where are completely more than 100 LTE networks in operation. Even more, in June there has been launched first LTE-Advanced network in the world by South Korean Telecom.

Number of LTE subscribers grows very fast. Until the end of 2013 there is expected about 134 million unique users, which is more than doubled last year.

Looking at the deployment in the Czech Republic, coverage by LTE is very poor and unsatisfactory. Since Czech MNOs do not have need to rush with the deployment, there are only few cities and part of Prague centre covered by LTE. Initialization of change comes from the government within the recommendation pack, so-called “Digitální Česko”, to support and keep competitiveness for future. This project also deals with effective utilization of frequency bands that remained after the transition to DVB-T. The bands suppose to be use only for LTE networks in the Czech Republic and they are subject to terms of Czech Telecommunications Office. Second round of the auction of digital dividend has been planned at the end of July and first bidding is expected in October this year. Since the auction offers perspective frequency bands, starting price is in tens to hundreds billions Czech crowns per block. Terms of the auction are set to increase a possibility to enter at least three new MNOs to Czech mobile market.

Future holders of the auction frequency bands must fulfil conditions linked to each auction block. They contain, among fulfilling of European standards, a limit values of EIRP, FDD duplex separation size, a minimum data rate in specified time period and way how to cover and launch LTE networks depends to district population density.

The auction is, for sure, going to shake up with the Czech mobile market and it expects to bring better services and higher data rates to vast majority of the Czech population. Due to grater competition and a connection fee reduction, the lower prices are expected then.

Backbone network is a big issue associated with LTE deployment in the Czech Republic. Since LTE networks provides downlink data rate up to 300Mbps, backbone networks are required to balance the data load and allowed a high data rates with low latency across the network. Links to cell sites are usually established by 100Mbps fibre link or by microwave. The most effective topology seems to be Mesh/Ring structure, features a recovery from any single link failure and providing X2 connection. For aggregation and core, DWDM systems can be used.

Unfortunately the Czech MNOs do not share any information about their backbone networks, business partners and readiness to LTE deployment, even as an unpublished part of this thesis.

References

[1] SCRASE, Adrian a John MEREDITH. ETSI MOBILE COMPETENCE CENTRE. *Overview of 3GPP Release 99: Summary of all Release 99 Features*. Summary of all Release 99 Features, 2004.

[2] KAPPLER, Cornelia. *UMTS networks and beyond.* Chichester, U.K.: John Wiley, 2009, xxxi, 353 p. ISBN 04-700-3190-5.

[3] 3G AMERICAS, *the Mobile Broadband Evolution: 3GPP Release 8 and Beyond* [HSPA+, SAE/LTE and LTE-Advanced]. February 2009

[4] 3G AMERICAS, *3GPP Mobile Broadband Innovation Path to 4G: Release 9, Release 10 and Beyond* [HSPA+, LTE/SAE and LTE-Advanced]. February 2010

[5] 4G AMERICAS, *4G Mobile Broadband Evolution: Release 10,Release 11 and Beyond - HSPA+, SAE/LTE and LTE-Advanced*. October 2012

[6] Overview of the 3GPP Long Term Evolution Physical Layer. In: ZYREN, Jim. *Overview of the 3GPP Long Term Evolution Physical Layer* [online]. 2007 [ref. 2013-04-19]. Available from: http://www.freescale.com/files/wireless_comm/doc/white_paper/3GPPEVOLUTIONWP.pdf

[7] ČESKÝ TELEKOMUNIKAČNÍ ÚŘAD. *Český Telekomunikační Úřad* [online]. 2013 [ref. 2013-04-20]. Available form: http://www.ctu.cz

[8] HOWARD, Michael. INFONETICS RESEARCH, Inc. Infonetics Research White Paper: Using Carrier Ethernet to Backhaul LTE. [online], February 2011. Available from: http://www.infonetics.com/whitepapers/2011-infonetics-research-whitepaper-using-carrier-ethernet-to-backhaul-lte.pdf

[9] DAHLMAN, Erik. *3G evolution: HSPA and LTE for mobile broadband*. 2st ed. Amsterdam: Elsevier ; Academic Press, 2008, xli, 608 s. ISBN 978-0-12-374538-5

[10]HOLMA, Harri, Antti TOSKALA, Karri RANTA-AHO a Juho PIRSKANEN. NOKIA SIEMENS NETWORKS. *IEEE Communications Magazine: High Speed Packet Access Evolution in 3GPP Release 7*. December 2007.

[11]4G AMERICAS. *The Evolution of HSPA: The 3GPP standards progress for fast mobile broadband using HSPA+*. 2011.

[12] *IEEE Communication Magazine: Relay technologies for WiMax and LTE-advanced mobile systems*. October 2009.

[13]SEIDEL, Eiko. 3GPP LTE-A Standardisation in Release 12 and Beyond. *Novel Mobile Radio Research*. January 2013, s. 1-9.

[14]HOYMANN, Christian, Daniel LARSSON, Havish KOORAPATY a Jung-Fu (Thomas) CHENG. LTE Technology Update: Part 2: A Lean Carrier for LTE. *IEEE Communications Magazine*. February 2013, s. 74-81.

[15]3GPP. *TS 25.212 V7.11.0 Technical Specification Group Radio Access Network: Multiplexing and channel coding (FDD) Release 7*. September 2009

[16]3GPP. *TS 36.212 V10.8.0 Technical Specification Group Radio Access Network: Evolved Universal Terrestrial Radio Access (E-UTRA)Multiplexing and channel coding Release 10*. June 2013.

[17]3GPP. *TS 25.213 V7.7.0 Technical Specification Group Radio Access Network: Spreading and modulation (FDD) Release 7*. December 2009

[18]3GPP. *TS 36.211 V10.7.0 Technical Specification Group Radio Access Network: Evolved Universal Terrestrial Radio Access (E-UTRA) Physical channels and Modulation Release 10*. February 2013.

[19]Czech Republic. Český telekomunikační úřad: Vyhlášení výběrového řízení za účelem udělení práv k využívání rádiových kmitočtů k zajištění veřejné komunikační sítě v pásmech 800 MHz, 1800 MHz a 2600 MHz. In: *ČTÚ-120 780/2012-613*. 2012. Dostupné z: http://www.ctu.cz/cs/download/vyberova_rizeni/vyhlaseni_vyberoveho_rizeni_12_07_2012.pd

[20]European Union. Rozhodnutí Komise: O harmonizovaných technických podmínkách využívání kmitočtového pásma 790–862 MHz pro zemské systémy k poskytování služeb elektronických komunikací v Evropské unii. In: *2010/267/EU*. 6th May 2010. Dostupné z: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:117:0095:0101:CS:PDF

[21]EUROPEAN COMMUNICATIONS OFFICE. *Documentation Database*. 2010. Dostupné z: http://www.erodocdb.dk/default.aspx

[22]European Union. Prováděcí rozhodnutí komise: kterým se mění rozhodnutí 2009/766/ES o harmonizaci kmitočtových pásem 900 MHz a 1 800 MHz pro zemské systémy schopné poskytovat celoevropské služby elektronických komunikací ve Společenství. In: *2011/251/EU*. 2011. Dostupné z: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:106:0009:0010:CS:PDF

[23]European Union. ECC Reccommendation (08)02: Frequency planning and frequency coordination for GSM / UMTS / LTE / WiMAX Land Mobile systems operating within the 900 and 1800 MHz bands. In: *ECC REC (08)02*. 2012. Dostupné z: http://www.erodocdb.dk/docs/doc98/official/pdf/Rec0802.pdf

[24] European Union. Rozhodnutí komise: o harmonizaci kmitočtového pásma 2 500 – 2 690 MHz pro zemské systémy k poskytování služeb elektronických komunikací ve Společenství. In: *2008/477/ES*. 2008. Dostupné z: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:163:0037:0041:CS:PDF

[25]European Union. ECC Reccommendation (11)05: Frequency planning and frequency coordination for terrestrial systems for Mobile/Fixed Communication Networks (MFCN) capable of providing electronic communications services in the frequency band 2500-2690 MHz. In: *ECC REC (11)05*. 2011. Dostupné z: http://www.erodocdb.dk/docs/doc98/official/pdf/Rec1105.pdf

[26]3GPP. *TS 36.213 V9.3.0 Technical Specification Group Radio Access Network: Evolved Universal Terrestrial Radio Access (E-UTRA) Physical layer procedures Release 9*. September 2010.

[27]4G AMERICAS. *Subscription forecast* [online]. 2012. Dostupné z: http://www.4gamericas.org/

List of Attachments

Attachment.A: List of LTE networks in service – Americas (April 13, 2013)

Country	Operator/Network Name	LTE in Service	LTE Band
Americas			
USA	MiSpot / Agri-Valley (CDMA) (Michigan)	**Mar-13**	LTE-700
	Alaska Communications (CDMA)	**Nov-12**	LTE-700
	AT&T Mobility	**Sep-11**	LTE-700, 2100 & AWS
	BendBroadband	**May-12**	LTE-1700/2100
	Bluegrass Cellular (Rural CDMA)	**Nov-12**	LTE-700
	Cellcom (WI, MI) (Rural CDMA)	**May-12**	LTE-700
	C Spire Wireless Cellular South (CDMA)	**Sep-12**	LTE-1700, 1900
	Cross Wireless/Sprocket (Rural CDMA)	**Nov-12**	LTE-700
	Leap Wireless/Cricket Comm. (CDMA)	**Dec-11**	LTE-1900, 2100 (IV)
	Metro PCS (CDMA)	**Sep-10** **VoLTE Aug 2012**	LTE-1900,2100 (IV)
	Mosaic Telecom (Rural CDMA)	**Jul-11**	LTE 700 & AWS
	Panhandle (PTCI) Bonfire	**Mar-12**	LTE-700
	Pioneer Cellular (OK) (Rural CDMA)	**May-12**	LTE-700
	Shenandoah Telecommunications	**Nov-12**	LTE-700
	Sprint & Affiliates (WiMAX)	**Jul-12**	LTE 850, 1900
	Strata Networks (Rural CDMA)	**Nov-12**	LTE-700
	Peoples & Etex Telephone Coop (Texas)	**Feb-12**	LTE-700
	T-Mobile USA	**Mar-13**	LTE-2100
	Thumb Cellular (Rural CDMA)	**Dec-12**	LTE-700
	US Cellular/King Street Wireless	**Mar-12**	LTE-700/2100 (IV)
	Verizon Wireless	**Dec-10**	LTE 700/2100 (IV)
Canada	Bell Wireless Affiliates	**Sep-11**	LTE-2100 (IV)
	Telus	**Feb-12**	LTE-2100 (IV)
	Eastlink Wireless	**Feb-13**	LTE-2100 (IV)
	MTS Mobility /Allstream	**Sep-12**	LTE-2100 (IV)
	Rogers Wireless Communications	**Jul-11**	LTE-1700/2100 (IV)
	SaskTel Mobility	**Jan-13**	LTE-2100 (IV)
Antigua & Barbuda	Digicel	**Nov-12**	LTE-700 TDD
Bolivia	Movil de Entel	**Dec-12**	LTE-700
Brazil	Claro	**Dec-12**	LTE-2600 FDD
	On Telecomunicações	**Mar-13**	LTE-2500 TDD
	Sky Telecom (Broadband)	**Dec-11**	LTE-2500 TDD
Colombia	UNE (EPM Telecomunicaciones)	**Jun-12**	LTE-2600
Dominican Rep.	Orange Dominicana	**Jul-12**	LTE-1800
	Tricom (CDMA to LTE)	**Mar-13**	LTE-1900
Mexico	Telcel	**Nov-12**	LTE-1700/2100
	Movistar	**Oct-12**	LTE-1700/2100
Paraguay	COPACO / VOX	**Feb-13**	LTE-1700/2100
	Personal / Núcleo	**Feb-13**	LTE-1900
Puerto Rico	AT&T Mobility	**Nov-11**	LTE-1700/2100
	Claro	**Dec-11**	LTE-700
	Open Mobile	**Apr-12**	LTE-700
	Sprint Nextel Puerto Rico	**Dec-12**	LTE-850, 1900
Uruguay	Antel	**Dec-11**	LTE-1700/2100

List of LTE networks in service – Asia Pacific and Oceania (April 13, 2013)

Country	Operator/Network Name	LTE in Service	LTE Band
Asia Pacific and Oceania			
Australia	NBN Co.	**Apr-12**	LTE-2300 TDD
	Optus (SingTel)	**Jul-12**	LTE-1800, 2100
	Telstra	**Sep-11**	LTE-1800
Guam	DoCoMo Pacific Guam	**Oct-12**	LTE-700
	iConnect Guam	**Mar-13**	LTE-700
	IT&E Guam	**Jul-12**	LTE-700
China - Hong Kong	CSL New World	**Nov-10**	LTE-1800, 2600
	Hutchison 3 / JV Genius	**May-12**	LTE-2600 FDD & TDD
	PCCW Mobile / JV Genius	**May-12**	LTE-2600
	SmarTone-Vodafone	**Aug-12**	LTE-1800
	China Mobile Hong Kong	**Apr-12**	LTE-2600 FDD & TDD
China - Singapore	MobileOne/M1 3G	**Jun-11**	LTE-1800, 2600
	SingTel Mobile/Mobile Prestige 75	**Dec-11**	LTE-1800, 2600
	StarHub	**Sep-12**	LTE-1800
India	Bharti Airtel	**Apr-12**	LTE-2300 TDD
Japan	eAccess / emobile	**Mar-12**	LTE-1800
	KDDI / au (CDMA)	**Sep-12**	LTE-800, 1500, 2100
	NTT DoCoMo / Xi	**Dec-10**	LTE-2100
	Softbank Mobile	**Feb-12**	LTE-2500 TDD
Malaysia	Maxis Communications/UMTS	**Jan-13**	LTE-2600
New Zealand	Vodafone New Zealand	**Feb-13**	LTE-700, 2100
Philippines	Globe Telecom/SingTel	**Sep-12**	LTE-1800
	Smart Communications	**Apr-11**	LTE-850, 1800, 2100
South Korea	KT Corp	**Jan-12**	LTE-1800
	LG Uplus	**Jul-11** **VoLTE Aug 2012**	LTE-850
	SK Telecom	**Jul-11** **VoLTE Aug 2012**	LTE-850, 1800 LTE-A in 2013
Sri Lanka	Dialog Axiata	**Jan-13**	LTE-1800 FDD/TDD
	Mobitel M3	**Jan-13**	LTE-1800

List of LTE networks in service – Europe (April 13, 2013)

Country	Operator/Network Name	LTE in Service	LTE Band
Europe			
Austria	Hutchison 3 Austria	**Nov-11**	LTE-2600
	A1 Telekom/Mobilkom (Telekom Austria)	**Oct-10**	LTE-2600
	T-Mobile Austria	**Jul-11**	LTE-2600
Belgium	Belgacom Mobile/Proximus	**Nov-12**	LTE-1800
Croatia	Hrvatski Telekom (T-Mobile)	**Mar-12**	LTE-1800
	VIPnet	**Mar-12**	LTE-1800
Czech Republic	Telefonica O2 Czech Republic	**Jun-12**	LTE-1800
Denmark	HI3G Denmark / 3	**Sep-12**	LTE-1800, 2600
	TDC Mobil	**Dec-10**	LTE-2600
	TeliaSonera Denmark	**Dec-10**	LTE-800,1800,2600
Estonia	EMT / Telia Sonera	**Jan-12**	LTE-1800, 2600
	Tele2	**Nov-12**	LTE-1800, 2600
Finland	DNA Finland/Oy	**Dec-11**	LTE-1800, 2600
	Elisa	**Dec-10**	LTE-1800, 2600
	TeliaSonera	**Nov-10**	LTE-1800, 2600
France	Orange France	**Jan-13**	LTE-800, 2600
	SFR	**Nov-12**	LTE-800, 2600
Germany	O2/Telefonica)	**Jul-11**	LTE-800
	T-Mobile / DeutscheTelekom	**Apr-11**	LTE-800, 1800
	Vodafone D2	**Dec-10**	LTE-800/2600 (DigDiv)
Greece	Cosmote	**Nov-12**	LTE-1800
	Vodafone / Panafone	**Dec-12**	LTE-1800
Hungary	T-Mobile Hungary	**Jan-12**	LTE-1800
	Telenor Hungary	**Jul-12**	LTE-1800
Iceland	Nova	**Apr-13**	LTE-800
Italy	3 Italy	**Nov-12**	LTE-1800
	Telecom Italia/TIM	**Nov-12**	LTE-1800
	Vodafone Italia / Omnitel	**Oct-12**	LTE-1800
Latvia	LMT - Latvijas Mobilais Telefons	**Jul-12**	LTE 1800
Lithuania	Omnitel (TeliaSonera)	**May-11**	LTE-1800
	Tele2	**Mar-13**	LTE-2600
Luxembourg	Tango (Belgacom)	**Oct-12**	LTE-1800
	Orange (Mobistar)	**Oct-12**	LTE-1800
Moldova	InterDnestrCom (IDC)	**Apr-12**	LTE-800
	Moldcell (TeliaSonera)	**Nov-12**	LTE-2600
	Orange	**Nov-12**	LTE-2600
Montenegro	Telenor / Promonte (LTE in Cetinje)	**Nov-12**	LTE-2600
Netherlands	KPN Mobile	**May-12**	LTE-2600
	T-Mobile Netherlands	**May-12**	LTE-2600
	Vodafone Libertel	**May-12**	LTE-2600
	Tele2	**May-12**	LTE-2600
	Ziggo 4	**May-12**	LTE-2600
Norway	Netcom/Telia Sonera	**Dec-09**	LTE-2600
	Telenor	**Oct-12**	LTE-2600

Country	Operator/Network Name	LTE in Service	LTE Band
Poland	Aero 2	**Sep-10**	
	Polkomtel / Plus	**Dec-11**	LTE-1800
	Sferia (CDMA)	**Jan-13**	LTE-850
Portugal	Optimus Sonaecom	**Mar-12**	LTE-800, 1800, 2600
	TMN	**Mar-12**	LTE-800, 2600
	Vodafone Portugal	**Feb-12**	LTE-800, 2600
Romania	Orange Romania	**Dec-12**	LTE-1800
	Vodafone Romania	**Nov-12**	LTE-800, 1800, 2600
Russia	Mobile TeleSystems /MTS	**Sep-12**	LTE-800, 2600 TDD
	Yota Networks	**May-12**	LTE-2500, 2600
Slovak Republic	Telefónica O2	**Aug-12**	LTE-1800
Slovenia	Mobitel - Telekom Slovenije	**Mar-13**	LTE-800, 1800, 2600
	Si.mobil	**Jul-12**	LTE-1800
Sweden	HI3G/3 Sweden	**Apr-12**	LTE 800,2600 FDD & TDD
	Net4Mobility TeleNor/Tele2	**Nov-10**	LTE 800, 900, 2600
	TeliaSonera Sweden	**Dec-09**	LTE 800, 1800, 2600
Switzerland	Swisscom Mobile/Natel	**Nov-12**	LTE 800, 1800, 2600
UK	EE/ Everything Everywhere /(Orange + T-Mobile)	**Oct-12**	LTE-1800
	UKB / UK Broadband (Wholesale)	**Jun-12**	LTE-3500 TDD

List of LTE networks in service – Middle East and Africa (April 13, 2013)

Country	Operator/Network Name	LTE in Service	LTE Band
Middle East and Africa			
Angola	Movicel	**Apr-12**	LTE-1800
	Unitel	**Dec-12**	LTE-2100
Armenia	K-Telecom/VivaCell-MTS	**Dec-11**	LTE-2600 FDD
Azerbaijan	Azercell	**Jun-12**	LTE 1800
Bahrain	Batelco	**Mar-13**	LTE-1800
Kazakhstan	Kazakhtelecom/Altel	**Jan-13**	LTE-1800
Kuwait	Kuwait Telecom Company/VIVA	**Dec-11**	LTE-1800
	Zain	**Nov-12**	LTE-1800
Kyrgyzstan	Saima Telecom	**Dec-11**	LTE-2600
Mauritius	Emtel Mauritius	**May-12**	LTE-1800
	Orange Mauritius	**Jun-12**	LTE-1800
Namibia	MTC	**May-12**	LTE-1800
Oman	Nawras	**Feb-13**	
	Omantel/Oman Mobile	**Jul-12**	LTE-1800,2300 FDD/TDD
Saudi Arabia	Etihad Etisalat/Mobily	**Sep-11**	LTE-2600 TDD
	Saudi Telecom Company / Al-Jawwal	**Sep-11**	LTE-1800 TDD
	Zain	**Sep-11**	LTE-1800
South Africa	MTN	**Dec-12**	LTE-1800, 2100
	Vodacom	**Oct-12**	LTE-1800
Tadjikistan	Babilon Mobile	**Sep-12**	LTE-1800, 2100
Tanzania	SMILE	**Jun-12**	LTE-850
UAE	du	**Jun-12**	LTE-1800
	Etisalat	**Sep-11**	LTE-1800, 2600
Uganda	Smile Telecom (WiMAX)	**Oct-12**	LTE-800
Uzbekistan	MTS-Uzbekistan	**Jul-10**	LTE-2600
	Ucell/TeliaSonera	**Aug-10**	LTE-2600
	Unitel LLC Beeline	**Feb-12**	LTE-2600

List of districts belong to Group A

Group A	Region	Population
Jeseník	Olomoucký kraj	41 095
Rokycany	Plzeňský kraj	47 207
Prachatice	Jihočeský kraj	51 471
Tachov	Plzeňský kraj	53 407
Rakovník	Středočeský kraj	55641
Domažlice	Plzeňský kraj	60 780
Plzeň-jih	Plzeňský kraj	61 655
Český Krumlov	Jihočeský kraj	61 706
Písek	Jihočeský kraj	70 673
Strakonice	Jihočeský kraj	70 807
Pelhřimov	Vysočina	72875
Plzeň-sever	Plzeňský kraj	75 470
Kutná Hora	Středočeský kraj	75 004
Rychnov nad Kněžnou	Královéhradecký kraj	79 152
Jičín	Královéhradecký kraj	80 165
Louny	Ústecký kraj	87 220
Klatovy	Plzeňský kraj	88 641
Jindřichův Hradec	Jihočeský kraj	93 180
Benešov	Středočeský kraj	94 652
Cheb	Karlovarský kraj	95 321
Havlíčkův Brod	Vysočina	95 679
Bruntál	Moravskoslezský kraj	97 369
Tábor	Jihočeský kraj	103 070
Česká Lípa	Liberecký kraj	104 278
Svitavy	Pardubický kraj	105 209
Příbram	Středočeský kraj	112 578
Jihlava	Vysočina	112 707
Znojmo	Jihomoravský kraj	113 720
Třebíč	Vysočina	113 590
Karlovy Vary	Karlovarský kraj	119 289
Žďár nad Sázavou	Vysočina	119 718
Šumperk	Olomoucký kraj	124 246

List of districts belong to Group B

Group B	Region	Population
Praha	Hlavní město Praha	1 257 158
Brno-město	Jihomoravský kraj	371 371
Ostrava - město	Moravskoslezský kraj	333 579
Karviná	Moravskoslezský kraj	270 412
Olomouc	Olomoucký kraj	232 226
Frýdek-Místek	Moravskoslezský kraj	212 100
Brno-venkov	Jihomoravský kraj	203 216
Zlín	Zlínský kraj	192 639
České Budějovice	Jihočeský kraj	187 799
Plzeň-město	Plzeňský kraj	184 885
Opava	Moravskoslezský kraj	177 236
Liberec	Liberecký kraj	170 410
Pardubice	Pardubický kraj	168 446
Hradec Králové	Královéhradecký kraj	163 378
Kladno	Středočeský kraj	160472
Hodonín	Jihomoravský kraj	156 524
Nový Jičín	Moravskoslezský kraj	152 524
Vsetín	Zlínský kraj	145 464
Uherské Hradiště	Zlínský kraj	144 203
Praha-východ	Středočeský kraj	146 403
Ústí nad Orlicí	Pardubický kraj	139 114
Děčín	Ústecký kraj	135 238
Přerov	Olomoucký kraj	133 932
Teplice	Ústecký kraj	129 932
Chomutov	Ústecký kraj	127 218
Mladá Boleslav	Středočeský kraj	122 816
Ústí nad Labem	Ústecký kraj	121 699
Trutnov	Královéhradecký kraj	119 814
Litoměřice	Ústecký kraj	117 941
Most	Ústecký kraj	116 797
Praha-západ	Středočeský kraj	120 990
Břeclav	Jihomoravský kraj	113 842
Náchod	Královéhradecký kraj	112 294
Prostějov	Olomoucký kraj	110 182
Kroměříž	Zlínský kraj	108 055
Blansko	Jihomoravský kraj	106 884
Chrudim	Pardubický kraj	104 395
Mělník	Středočeský kraj	102 628
Kolín	Středočeský kraj	95 764
Sokolov	Karlovarský kraj	92 834
Nymburk	Středočeský kraj	92 679
Jablonec nad Nisou	Liberecký kraj	90 569
Vyškov	Jihomoravský kraj	89 097
Beroun	Středočeský kraj	85 081
Semily	Liberecký kraj	74 685