LTE – Long Term Evolution of Mobile Radio Communications

Grega Jakus, Saso Tomazic

Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia

Keywords: *LTE, SAE, Mobile Communications, OFDM, E-UTRAN, 3GPP*

Definition: *LTE is a mobile radio access technology specified by the 3GPP. LTE is an evolution of GSM and UMTS, and can be considered the last major step towards the fourth generation of mobile radio systems.*

Abstract: LTE is an evolution of GSM (*Global System for Mobile Communications*) and UMTS (*Universal Mobile Telecommunications System*). LTE introduces a new radio access network that implements technologies which provide higher data rates, improvements in efficiency and quality of service, lower costs and integration with existing open standards. The LTE radio access network is connected with a core network known as SAE (*System Architecture Evolution*) that implements flat network architecture and is exclusively packet switched.

Introduction

Mobile networks have become an important means of Internet access recently, although these networks were primarily designed for voice transmission between two users. With the establishment of the third generation of mobile networks (e.g. UMTS, CDMA2000) and their upgrades (e.g. HSPA, EV-DO), data rates have been continuously increasing but still have not reached those of fixed networks. At the same time, the amount of user data transferred and the number of mobile Internet users have also increased.

The increasing amount of transferred data and new applications such as mobile games and television, Web 2.0 and video streaming have motivated the 3GPP (*Third Generation Partnership*

Project) organization to start the LTE project. The project's aim is to issue a series of recommendations (called *Release 8*) for new radio access that will support recent trends in mobile communications. Although often designated as a fourth-generation mobile technology, LTE actually does not yet meet the requirements to be a 4G mobile network [1], [2] so it is often designated as 3.9 G. Nevertheless, LTE will bring improvements in efficiency and quality of service, lower operator costs, better utilization of the frequency spectrum and integration with existing open standards. LTE will introduce characteristics to mobile networks similar to those in fixed networks.

Features and capabilities

The LTE project targets the following features and capabilities of the evolved radio access network (E-UTRAN, *Evolved Universal Terrestrial Radio Access Network*) [3]:

- Peak data rates of 100 Mb/s on the downlink and 50 Mb/s on the uplink within a 20 MHz spectrum allocation.
- Control plane capable of carrying signalization for 200 simultaneously active users for spectrum allocations up to 5 MHz and for at least 400 users for higher spectrum allocations.
- Switch time between idle and active state shorter than 100 ms.
- Radio access network latency below 10ms.
- Spectral efficiency 5 bit/s/Hz on the downlink and 2.5 bit/s/Hz on the uplink.
- Radio access network optimized for mobile user speeds up to 15 km/h. The system should support high performance for speeds up to 120 km/h. Links should be maintained at speeds up to 350 km/h, or up to 500 km/h depending on the frequency band.

- The system should support the targeted performance within a 5 km range. A slight degradation in performance is tolerated within a 30 km range. Ranges up to 100 km or even more should not be precluded by the specifications.

- Enhanced broadcast and multicast transmissions compared to HSPA standards.

- Scalable bandwidth allocation of 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. Bandwidths narrower than 5 MHz enable a smooth transition to the spectrum of the previous generations of mobile systems.

- Deployment in frequency bands of the previous generations of mobile systems: 450 MHz, 700 MHz, 800 MHz, 900 MHz, 1600 MHz, 1700 MHz, 1900 MHz, 2100 MHz and other. Because a large set of frequency bands is available, global roaming will be possible.

- Support for paired and unpaired spectrum for FDD (*Frequency Division Duplex*), TDD (*Time Division Duplex*) and the combination of both. The advantage of combined TDD and FDD use are simplified terminals at the expense of higher data rates that could be achieved with the frequency duplex.

- Interoperability with existing mobile systems at the same location on adjacent channels. The time needed for handover between E-UTRAN and other radio access networks must be shorter than 300 ms for real time services and 500 ms for other services.

- The architecture of E-UTRAN must be packet-based, but it must also support real-time services.

- Support for various types of services (e.g. Voice over IP (VoIP), data transfer).

- Reasonable system and terminal complexity, cost and power consumption.

Key technologies

LTE is based on existing technologies that were not widely used in mobile communications in the past. The reason is their large processing requirements, which, due to technological progress, are no longer problematic. LTE introduces new models of multiplexing and multiple access techniques on a radio interface, such as OFDM (*Orthogonal Frequency Division Multiplex*) and OFDMA (*Orthogonal Frequency Division Multiple Access*) on the downlink and SC-FDMA (*Single Carrier Frequency Division Multiple Access*) on the uplink.

OFDM has proved to be a successful technology in many wired and wireless systems, such as DAB (*Digital Audio Broadcast*), DVB (*Digital Video Broadcast*), WLAN (*Wireless Local Area Network*, IEEE 802.11a and g), WiMAX (IEEE 802.16) and ADSL (*Asymmetric Digital Subscriber Line*). OFDM does not require complex equalization techniques to eliminate distortions of the radio signals and can be used with various bandwidths.

Advanced antenna techniques, such as MIMO (*Multiple-Input Multiple-Output*), are also important in LTE. MIMO increases radio network throughput by transmitting multiple data streams simultaneously within the same frequency band. The signals propagate along different paths, which is a common phenomenon in mobile communications. The receiver separately receives the signals with different delays, creating parallel channels.

OFDM downlink transmission

In mobile communications, single carrier modulations are most commonly used on the physical channel. Channel distortions are compensated with equalization in the time domain by *channel inversion* or with *rake equalizers*. Implementation of these principles is becoming complex with increasing bit rates. Because LTE data rates are perceptibly higher than in mobile systems in use today, a different principle for transmission on the physical layer must be used.

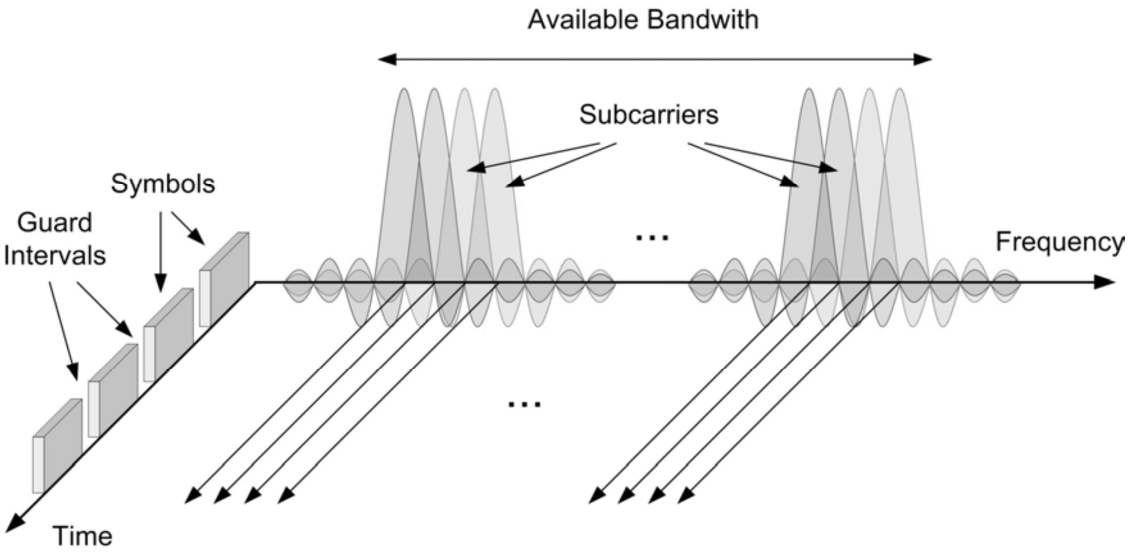

Figure 1: Representation of OFDM in the time and frequency domains

As opposed to single-carrier systems, OFDM does not demand higher symbol rates to achieve higher data rates [4], [5]. The available bandwidth is apportioned into a large number of narrow bands in which data are transmitted in parallel (Figure 1). In each of these bands, a subcarrier is modulated with a different level of QAM (*Quadrature Amplitude Modulation*), depending on the type of data and on the conditions on the radio interface in that particular frequency band. Each transmitted symbol is a linear combination of simultaneous signals that are transmitted by several subcarriers of the user's channel. Because the transmission is parallel rather than serial, the duration of data symbols can be perceptibly longer than in single-carrier modulations at the same data rate. A consequence of using longer symbols is less *intersymbol interference* (ISI).

In LTE, each OFDM symbol consists of a cyclic prefix and an FFT (*Fast Fourier Transform*) period in which data are carried (Figure 2). A cyclic prefix is transmitted during the guard interval and is important for the elimination of ISI. The length of the prefix depends on the maximum expected delay between two instances of a signal that arrive at the receiver along different paths. The period must be chosen so that one symbol affects the adjacent symbol only within the cyclic prefix but not within the FFT period.

The receiver determines the channel response on each subchannel on the basis of periodic transmissions of reference signals. The determined response is used for eliminating distortions on each subchannel separately. When the signal is received and digitalized, the receiver eliminates the cyclic prefix so that on each subchannel only a rectangular impulse remains. The rectangularity of the impulses is important for placing the subchannels closely next to one another without causing mutual interference (ICI, *Inter Carrier Interference*). The rectangular impulses in the time domain have the shape of a *sinc* function in the frequency domain (Figure 2). The length of the FFT period is deliberately chosen so that the zero-crossings in the spectrum are exactly at the position of the adjacent subcarriers (Figure 1), which results in no mutual interference among adjacent channels.

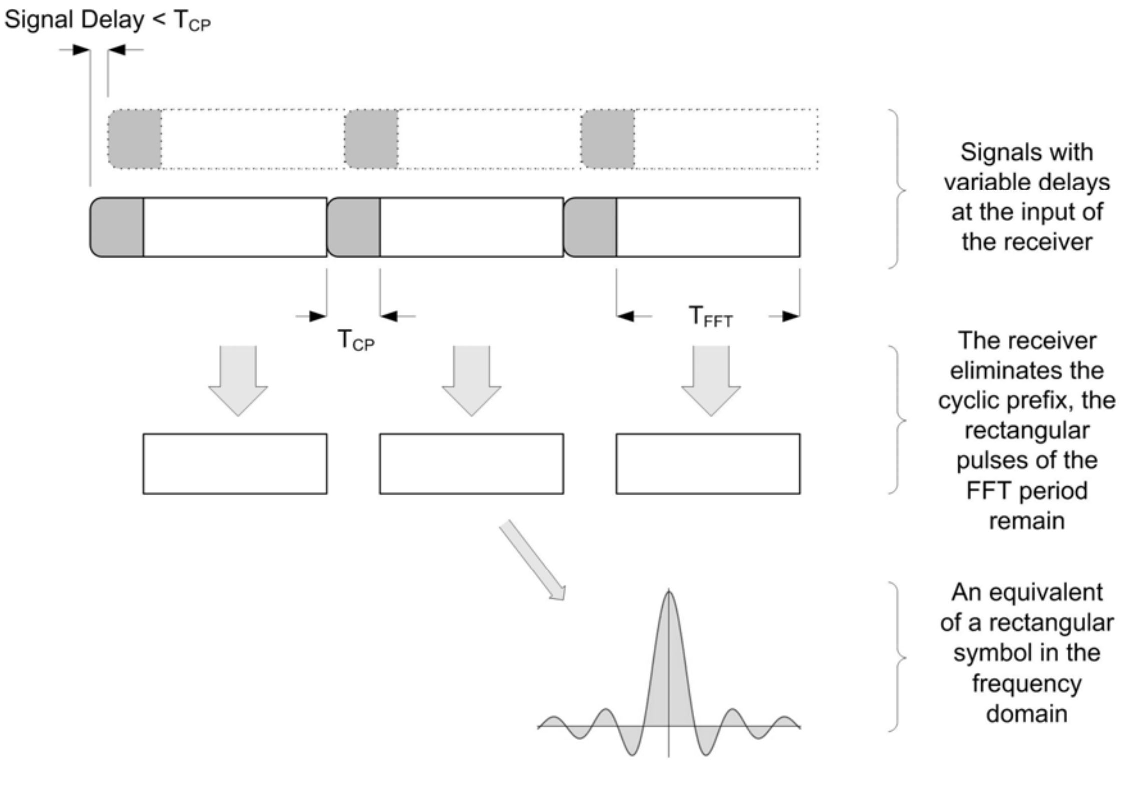

Figure 2: Elimination of ISI and ICI with the cyclic prefix and long rectangular symbols

A disadvantage of OFDM is its sensitivity to carrier frequency shifts (for instance caused by the Doppler shift) and high PAPR (*Peak to Average Power Ratio*), which results in inefficient energy consumption.

OFDMA multiple access and physical frame structure

In the OFDMA multiple access scheme, each user is assigned a number of subchannels for a certain number of time slots. The time slots and subchannels together compose "Physical Resource Blocks" (PRB) which have both a time and a frequency dimension [6]. A PRB consists of 12 consecutive subchannels that are allocated for the time of one time slot (0.5 ms). Short time slots assure small network delays. The number of available PRBs depends upon the available bandwidth.

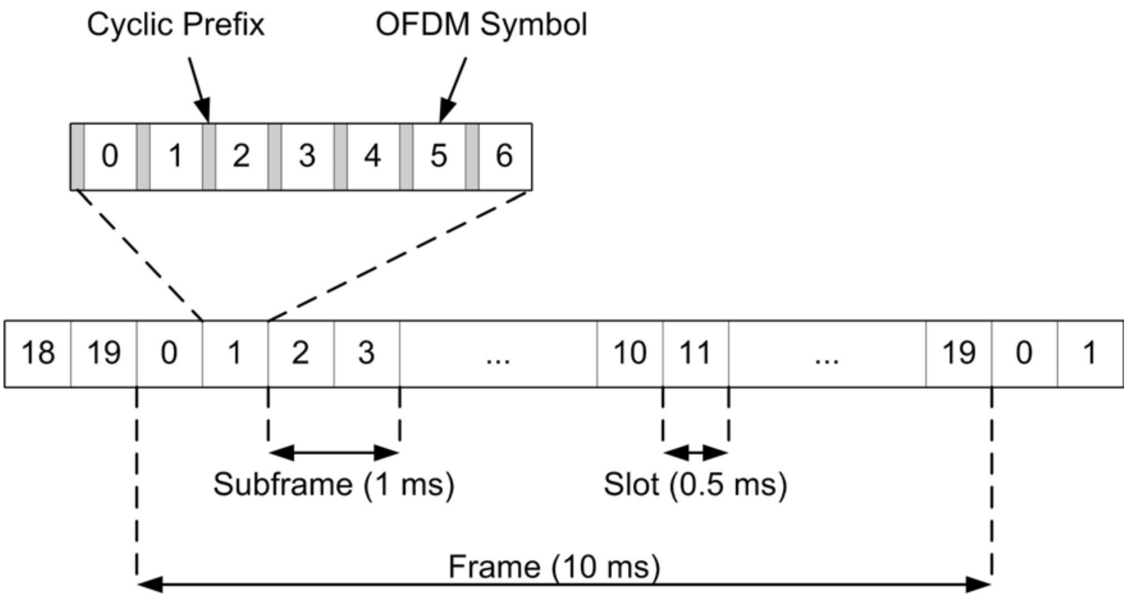

Figure 3: Generic frame structure on the physical layer

Time slots are combined into frames (Figure 3). Each frame has a length of 10 ms and is divided into ten subframes of equal size. A subframe consists of two equal-sized time slots. In a time slot, 6 or 7 OFDM symbols are carried depending on the length of the cyclic prefix.

SC-FDMA

Energy consumption is the most important factor for the choice of modulation on the uplink. One of the disadvantages of OFDM is high PAPR, which negatively affects battery life. Therefore, SC-FDMA with a lower PAPR is used as an alternative on the uplink.

The operation of SC-FDMA [4], [7] is in principle similar to OFDMA. The architecture of the transmitter and the receiver is almost identical, as is also the protection against multipath propagation distortions. Unlike OFDM, subcarriers are not individually modulated in SC-FDMA. The input data stream is spread prior to modulation over the bandwidth occupied by several subcarriers and then mapped to those subcarriers. However, the data are transmitted sequentially, rather than in parallel. The term "Single Carrier" thus refers to the sequential transmission of symbols over a single-frequency carrier, while "FDMA" refers to user multiplexing in the frequency domain.

Scheduling

Scheduling is the process of assigning physical resources to users. In LTE, scheduling, especially in the frequency domain, is important and can be achieved with two different approaches:

<u>Frequency diverse scheduling:</u> users are assigned subchannels that are spread over the available spectrum. The probability of poor channel conditions in two non-adjoining subchannels is smaller than in the case of consecutive subchannels.

<u>Frequency selective scheduling:</u> a user is assigned a frequency block with the best channel conditions, so that spectral efficiency is optimally high (Figure 4). The frequency block is

determined on the basis of the feedback information on channel quality that the mobile terminal reports to the base station.

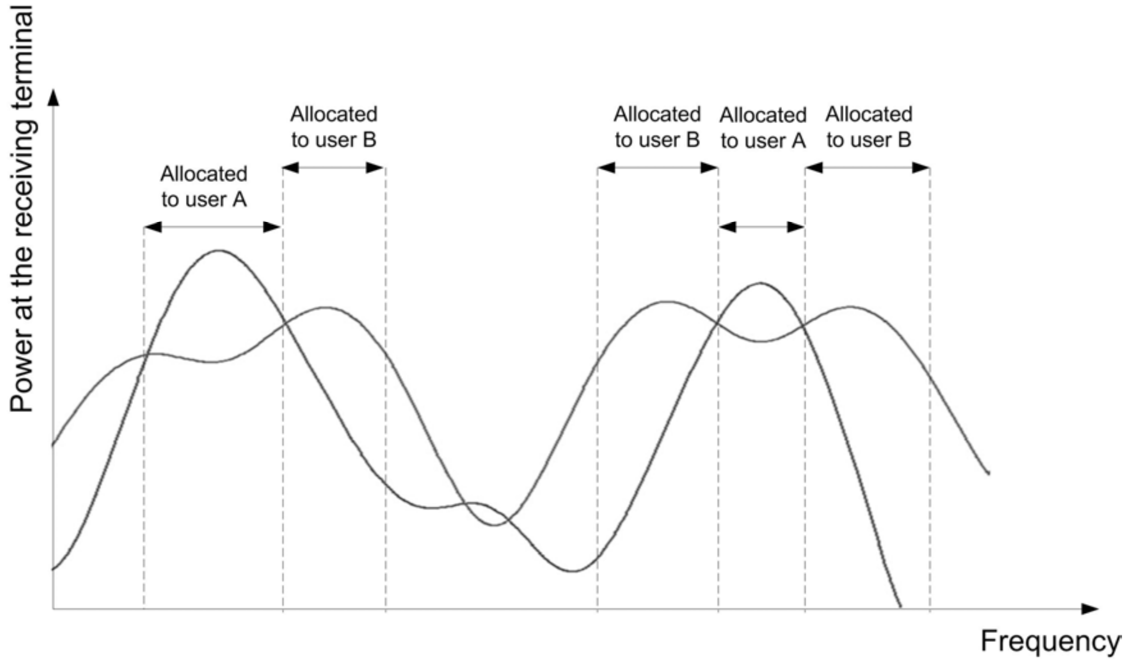

Figure 4: Frequency selective scheduling

On the downlink, frequency selective scheduling is used. The least resources a user can be assigned is two PRBs. Decisions about allocations are made every TTI interval of 1 ms and are sent to users on the control channel in the first OFDM symbols in every subframe.

Scheduling on the uplink is performed in the time domain (TDMA) or in combination with the frequency domain. In the frequency domain, a user can be allocated a block of adjoining subchannels or subchannels that are distributed over the available spectrum.

Advanced antenna technologies

To achieve high data rates, high capacity and extended coverage, LTE also uses advanced antenna solutions, such as MIMO and beamforming.

MIMO refers to the use of multiple antennas in wireless communications on both the transmitting and the receiving side. MIMO can be used in different modes, such as *spatial multiplexing, transmit diversity* and *cyclic delay diversity*.

Spatial multiplexing is the transmission of independent and separately coded data streams in parallel over non-correlated antennas. The radio channel ideally consists of N_{Tx} x N_{Rx} non-correlated paths, where N_{Tx} is the number of transmitting and N_{Rx} the number of receiving antennas. The transmitted streams belong to a single or several users, increasing the link throughput of a single user or the entire capacity on a certain frequency band. The theoretical increase factor of channel throughput is $min(N_{Tx}, N_{Rx})$ in environments with large signal scattering, while there is no gain in environments with direct visibility. The basic MIMO configuration in LTE on the downlink is two antennas on both the transmitting and the receiving side.

On the uplink, spatial multiplex changes to SDMA (*Spatial Division Multiple Access*), where several mobile terminals transmit on the same physical resources simultaneously. The mobile terminals primarily transmit with a single antenna, but transmission with two antennas is also supported.

Instead of increasing data rates, MIMO can also be used to increase the robustness of the transmission. This mode is known as *transmit diversity* and is usually employed when channel conditions do not allow spatial multiplexing. Each antenna transmits the same data stream with different channel coding, which is predefined and referred to as *Space-Frequency Block Coding*.

Cyclic delay diversity can be used in addition to spatial multiplexing. Each antenna transmits with a specific delay that is added to the signal, which creates an additional multipath delay and increases frequency diversity at the receiver.

The electromagnetic signal at the transmitting antenna can be formed into a beam, which is known as *beamforming*. By guiding the beam towards the user, faster transmission rates, control and reduction of interference from other users can be achieved, resulting in higher SNR (*Signal to Noise Ratio*) at the receiver. While MIMO increases channel throughput in the centre of a cell, beamforming increases channel throughput on the cell edges.

Signal processing on the physical layer

Prior to transmission, the signal is processed to optimally exploit radio channel conditions. The most important procedures are:

- 24-bit CRC (*Cyclic Redundancy Check*) coding;
- channel coding using turbo codes based on QPP inner interleaving with trellis termination;
- HARQ (*Hybrid Automatic Repeat reQuest*) processing for error detection and correction;
- QPSK, 16QAM or 64QAM modulation;
- scheduling – the assigning of time-frequency resources to a user, based on the target QoS (*Quality of Service*), signal quality, capabilities of the mobile terminal and the state of the buffer at the base station;
- mapping to assigned physical resources and antenna ports.

On the downlink, adaptive modulation and coding with different modulation schemes and bit rates are used, depending mostly on the quality of the received signal at the mobile terminal, which is reported to the network. The same modulation and coding are used for all PRBs that belong to the same PDU (*Protocol Data Unit*) of the link layer for a single user within a single TTI and data stream (e.g. transmitted from a single antenna).

Multimedia Broadcast Multicast Services and Single Frequency Network

An important functionality of LTE is Multimedia Broadcast and Multicast Services (MBMS). MBMS data can be transmitted within a single cell or among several cells. Multi-cell transmissions are synchronized and use a common frequency, and therefore this principle is also known as a Single Frequency Network (SFN). Mobile terminals can use soft combining of the signal received from multiple cells, which has a notable impact especially on the cell edges. The receiver deals with such signals in the same manner as with the delayed signals from a single base station. Because the delays between two signals originating from different cells can be larger than in single cell transmissions, tighter subcarrier spacing and a longer cyclic prefix are used.

By using the SFN concept, a mobile terminal can roam between cells without a handover. An example of a possible application of MBMS and SFN is mobile television over LTE infrastructure.

The upper layers of the LTE protocol stack

Figure 5 presents the structure of the link layer for the downlink [8]. The scheme for the uplink is similar. The service access points (SAPs) of the physical layer are known as the *transport channels*, while those of the MAC (*Media Access Control*) sublayer are known as *logical channels* and the SAPs of the link layer are *radio bearers*.

Transport channels correspond to services provided by the physical layer. These services are defined by how and with what characteristics data are transported over the radio interface.

Logical channels correspond to the data transfer services that are offered by the MAC sublayer and are defined by the type of information they carry. Logical channels are divided on the control channels that carry data on the control plane and traffic channels that carry the user plane data.

Radio bearers correspond to the type of information and quality of service at transmission on the radio interface, e.g. to VoIP, video streaming, file transfer and control plane communications.

The MAC sublayer [9] controls access to the physical medium. It performs the mapping among logical and transport channels, and the multiplexing/demultiplexing of these channels. It also performs radio resource allocation, priority handling and HARQ-based error corrections.

The RLC (*Radio Link Control*) [10] controls links on the radio interface, performs traffic control, segmentation and reassembly of data packets and error correction based on ARQ. It provides different modes of operation suitable for different radio bearers.

The PDCP (*Packet Data Convergence Protocol*) [11] converts the PDUs of the higher layers into a format suitable for transfer over the radio interface. It provides in-sequence delivery of PDUs and security mechanisms, and performs header compression of network-layer PDUs.

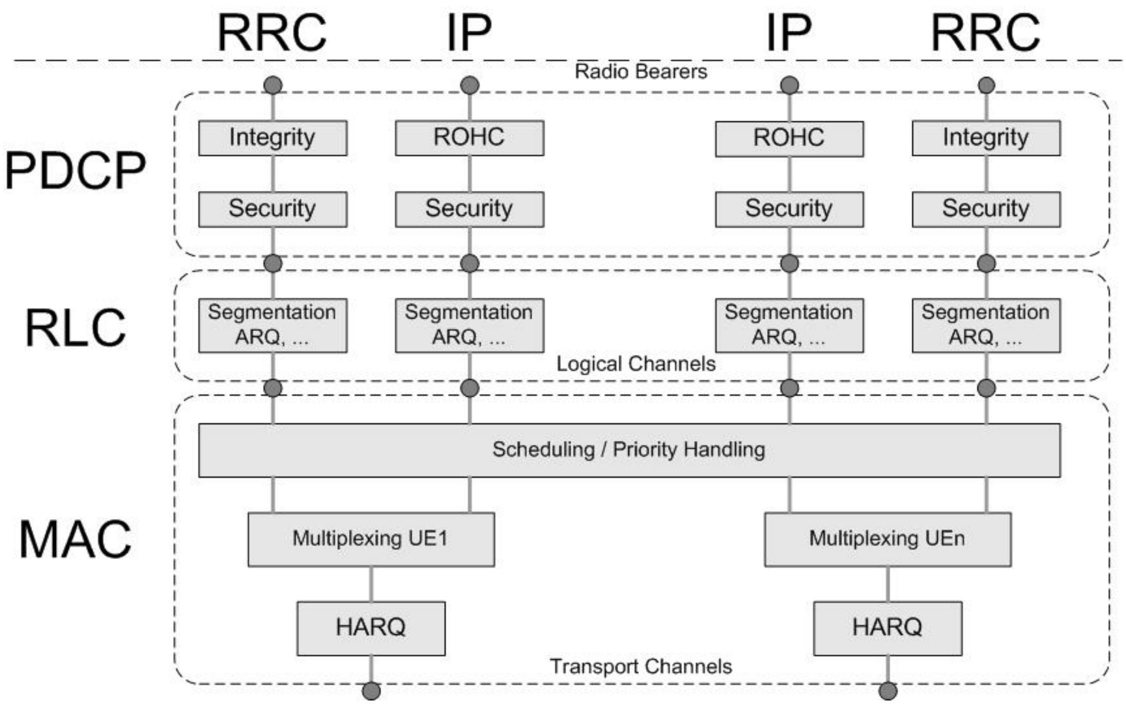

Figure 5: Link layer structure for the downlink

The RRC (*Radio Resource Protocol*) [12] is a network-layer protocol of the control plane that handles signalization. It supports the transmission of broadcast system information and dedicated control information, establishes and maintains services, and controls the QoS.

SAE – System Architecture Evolution

SAE is a core network architecture that supports the characteristics of LTE. SAE introduces a packet switched mobile core network (*Evolved Packet Core*, EPC) with the following elements:

- Serving Gateway (S-GW) and PDN (*Packed Data Network*) Gateway on the user plane; and
- *Mobility Management Entity* (MME) on the control plane.

The elements of EPC can be incorporated into one or more physical nodes, linked with standardized interfaces, which enable the use of hardware of various manufacturers. Figure 6 shows a simplified SAE network architecture.

SAE separates the user and the control plane. The latter is managed especially by the MME. Because there are no radio network controllers, as individual network elements in SAE, the base station (eNB, eNodeB) connects directly with the S-GW or MME for the exchange of user and control information (Figure 6). Besides routing data towards the EPC, the eNodeB also schedules and transmits paging messages, selects an MME during network attachment, etc. The eNodeB communicates with mobile terminals over link layer protocols and the RRC, and also implements the functionality of the physical layer presented in the previous sections.

MME is the key control node in the network. It performs the signalization and controls the entities in various layers of the protocol stack.

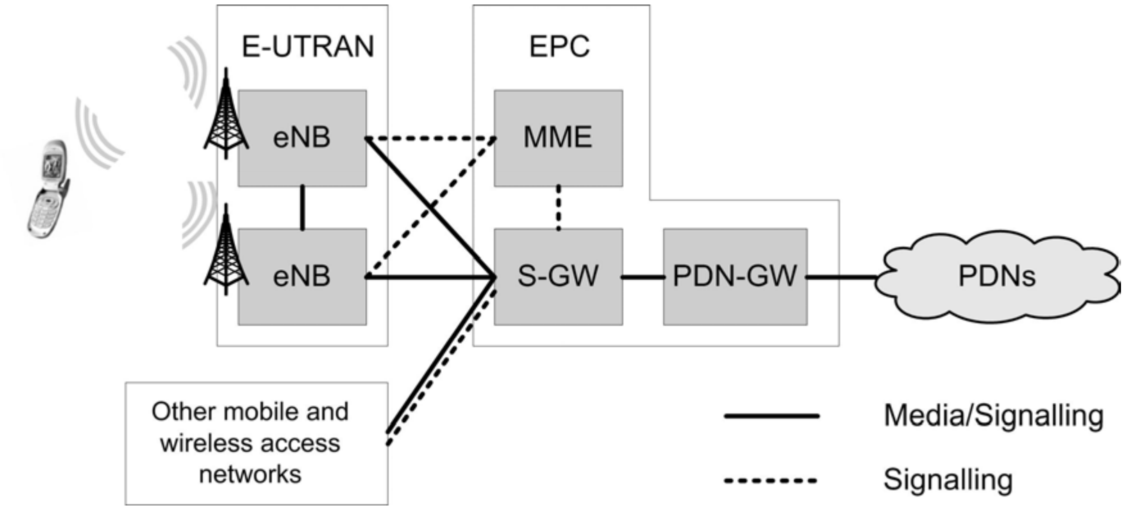

Figure 6: Architecture of LTE radio access (E-UTRAN) and core network (EPC)

The Serving Gateway supports mobility anchoring during inter-eNodeB handover and inter-3GPP network mobility. It also supports charging and performs routing, forwarding, buffering, marking and interception of data packets.

The PDN Gateway ensures the connectivity of the mobile terminal with other packet data networks. The functions of the PDN Gateway include filtering, intercepting and marking of data packets, DHCP (*Dynamic Host Configuration Protocol*), support for charging and traffic shaping.

Summary

The evolved radio access network and simplified network architecture offer higher data rates and better network responsiveness compared to existing 3G mobile systems. These improvements enable applications and services that were previously only available in fixed networks to enter the mobile world as well.

The enhanced mobile network will bring benefits to users, mobile operators and service providers. Users will benefit from improvements in existing services and from the introduction of new ones, and the user experience will also improve. Operators and service providers will be able to maintain their level of profitability despite the continuously falling prices of transferred data.

LTE standardization has come to a point where changes in specifications are limited to minor corrections and bug fixes. The first LTE networks are expected to be deployed in the beginning of 2010; however, the evolution of mobile networks continues even beyond LTE. *LTE-Advanced* [13], a successor to LTE, is already in the specification phase and is already considered a true 4G technology.

Links

1. 3GPP Homepage. http://www.3gpp.com/
2. ITU-T Homepage. http://www.itu.int/ITU-T/
3. 3G Americas Homepage. http://www.3gamericas.org/

References

1. ITU-R, "Requirements, evaluation criteria and submission templates for the development of IMT-Advanced", REPORT ITU-R M.2133, 2008.
2. ITU-R, "Requirements related to technical performance for IMT-Advanced radio interface(s)", REPORT ITU-R M.2134, 2008.
3. 3GPP, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN) (Release 8)", TR 25.913 V8.0.0, December 2008.
4. Rohde & Schwarz, "UMTS Long Term Evolution (LTE) Technology Introduction, Application Note 1MA111, Rohde & Schwarz", January 2008.
5. J. Zyren, W. McCoy, "Overview of the 3GPP LTE Physical Layer", Freescale Semiconductor, July 2007.
6. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Services provided by the physical layer (Release 8)", TS 36.302 V8.1.0, March 2009.
7. H. G. Myung, L. Junsung, and D. J. Goodman, "Single Carrier FDMA for Uplink Wireless Transmission", IEEE Vehicular Technology Magazine, Vol. 1, No. 3, September 2006, pp. 30-38.
8. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 8)", TS 36.300 V8.8.0, March 2009.
9. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) Medium Access Control (MAC) protocol specification (Release 8)", TS 36.321 V8.5.0, March 2009.
10. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) Radio Link Control (RLC) protocol specification (Release 8)", TS 36.322 V8.5.0, March 2009.
11. 3GPP, "Packet Data Convergence Protocol (PDCP) specification (Release 8)", TS 36.323 V8.5.0, March 2009.
12. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) Radio Resource Control (RRC); Protocol specification (Release 8)", TS 36.331 V8.5.0, March 2009.
13. 3GPP, "Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced) (Release 8)", TR 36.913 V8.0.1, March 2009.