LTE and Beyond

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Abstract In this chapter, we provide a brief yet comprehensive overview of current Long Term Evolution (LTE) systems and beyond. We begin presenting the baseline technology and the underlying features of network architecture, protocols, and air interface introduced in the first LTE release back in 2008. Having the basics put in place, we move forward to discuss advanced features introduced and further developed throughout subsequent LTE releases. Our discussion takes into consideration even the still under discussion LTE Release 13, which has in March 2016 its estimated freeze date.

1 Introduction

The wireless communications industry has been undergoing great developments since the beginning of this century. The second generation (2G) of cellular technology provided the possibility to increase the number of simultaneous phone calls, while sharing the same radio frequency (RF) spectrum. The third generation

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(3G) technology, based on wideband code-division multiple access, increased data transmission rates and improved voice services' quality. In recent years, standards such as Long Term Evolution (LTE) advanced by the 3G Partnership Project (3GPP), and IEEE 802.16e/m, also known as Worldwide Interoperability for Microwave Access (WiMAX), have improved the spectral efficiency of wireless channels thanks to the introduction of air interfaces based on orthogonal frequency-division multiplexing (OFDM). LTE has been regarded as the most important candidate to become the leading technology in fourth generation (4G) networks and beyond due to its popularity and continuous development of new features [1].

LTE is a highly flexible radio interface. Its first release defined the fundamental elements of the radio access network (RAN), which is composed of only one base station called evolved node B (eNodeB) providing user- and control-plane terminations toward the user equipment (UE) [2]. eNodeBs are interconnected and directly linked to a core network providing connection to other internet protocol (IP) based networks. This so-called flat architecture simplifies the user data flow and enables flexible, cost-effective capacity scaling [3]. LTE Rel. 8, the first release of the family of LTE standards, provides peak rates of 300 Mbps, latency below 10 ms, and a significant boost in spectrum efficiency as compared to previous cellular systems. It offers a scalable radio bandwidth, ranging from 1.4 to 20 MHz, and supports both frequency-division duplexing (FDD) and time-division duplexing (TDD) operations. Other important features relate to LTE cross-layer mechanisms, such as link adaptation, hybrid automatic repeat request (HARQ), and multiuser diversity through both time- and frequency-adaptive scheduling. The designed system also allows up to four spatial layers for single-user multiple input multiple output (MIMO) transmission [4].

On top of the basic framework put forth along the lines above, 3GPP introduced in LTE Rel. 9 features of location-based services, multimedia services both in broadcast and multicast formats, self-organizing and self-optimizing functionalities, dual layer beamforming, and additional support to new operating bands. Notwithstanding the importance of Releases 8 and 9, they are not intended to meet the requirements issued by the International Telecommunication Union on International Mobile Telecommunications (4G) systems. In contrast, the advanced version of LTE was developed bearing those requirements in mind so as to offer lower latency than the previous releases, peak data rates elevated to up to 3 Gbps in the downlink, operating bandwidth of up to 100 MHz in the downlink, and efficient interference management, just to mention some among a number of other advanced functionalities. The technology evolution continues with LTE Rel. 11 and LTE Rel. 12, which not only improve features already introduced in previous releases, but also introduce entirely new features. LTE Rel. 13 is still ongoing standardization work.

In this chapter, we provide a brief yet comprehensive overview of current LTE systems and beyond. The remainder of the chapter is organized as follows. Section 2 presents the baseline LTE technology and the underlying features of its network architecture, protocols, and air interface. Having these basics in place,

Sect. 3 discusses advanced features that have been introduced and further developed throughout subsequent LTE releases aiming at improving spectrum use, increase network density, and delivering other performance improvements. Two kinds of advanced services are dealt with in Sect. 4, as these have been receiving special attention within 3GPP. Section 5 wraps up the chapter with some concluding remarks.

2 Fundamentals of LTE

This section aims at providing a brief yet comprehensive overview about the LTE technology and its underlying features. The LTE network architecture, protocols, important system features, and air interface are described, putting in place the basic information on top of which the remainder of this chapter develops.

2.1 Architecture

The standardization effort of 3GPP has two primary objectives. The first objective was to create a common packet core network, the evolved packet core (EPC), to support mobile services, not only over 3GPP-defined radio access technology (RAT), but also over other standardized RATs, e.g., Wi-Fi. The second objective was to create a new radio access network, called evolved universal terrestrial radio access network (E-UTRAN), based on OFDM. The next subsection describes these important network elements.

2.1.1 Core Network

The requirements of the EPC are specified in [5]. As seen in Fig. 1, the EPC consists of two control-plane nodes, namely mobility management entity (MME) and home subscriber server, and three user-plane nodes, namely serving gateway (S-GW), packet-data network gateway (P-GW), and policy and charging rules function (PCRF). Also in Fig. 1, it is easily to figure out protocol stack interfaces between every node described in previous lines, for more detailed information refer to [6].

2.1.2 Access Network

The access network for normal user traffic does not have a centralized controller in E-UTRAN, so the architecture is said to be flat [7]. The eNodeB provides the radio interface and performs radio resource management (RRM), including

radio bearer control, radio admission control, and scheduling of uplink and down-
link radio resources for every UE. The eNodeB also supports IP header compres-
sion and encryption of the user plane data. All eNodeBs are interconnected to one
another via an interface X2; which has several uses, e.g., handover.

The other important aspect of LTE is that eNodeBs are connected to the EPC
via S1 interface, which is split into user and control planes. The control-plane
interface is referred to as S1-MME and terminates in the MME. The S1-U termi-
nates in the S-GW and supports pooling, which is a very important feature estab-
lishing a many-to-many relationship between the eNodeBs and the MMEs and the
S-GWs. The S1 interface also supports network sharing. This allows operators to
share the radio network, which are the eNodeBs, while maintaining their own EPC
networks.

The E-UTRAN is responsible for all radio-related functions, which can be sum-
marized as:

- RRM: RRM covers all functions related to the radio bearers, such as radio
  bearer control, radio admission control, radio mobility control, scheduling, and
  dynamic allocation of resources to UEs in both uplink and downlink [8];
- Header compression: This helps ensure efficient use of the radio interface by
  compressing IP packet headers, which could otherwise represent a significant
  overhead—especially in case of small packets, such as voice over IP [9];
- Security: All data sent over the radio interface is encrypted;
- Connectivity to the EPC: This consists of the signaling toward the MME and
  the bearer path toward the S-GW.

Fig. 1 EPC architecture adapted from [59]. *Dashed lines* represent the control plane, whereas *solid lines* represent the user plane
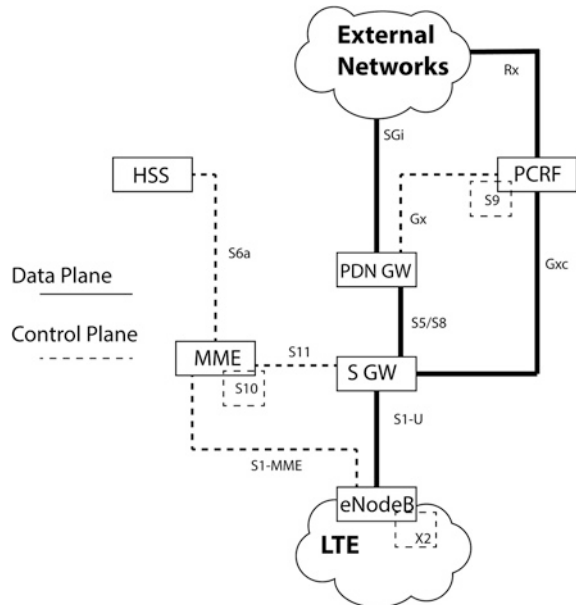
2.2 Control and User Plane Protocols

Figure 2 shows a general overview of the radio protocol architecture considered in LTE, as well as the use of radio bearers, logical channels, transport channels, and physical channels [10]. This figure provides a big picture of both control and data plane protocols, which are discussed in the sequel.

The dedicated radio resource control (RRC) messages that are transferred across signaling radio bearers (SRBs), which are mapped via the packet-data convergence protocol (PDCP) and radio link control (RLC) layers onto logical channels—either the common control channel (CCCH) during connection establishment or a dedicated control channel (DCCH) in RRC_connected state. Paging messages and system information are mapped directly onto logical channels: the paging control channel (PCCH) and broadcast control channel (BCCH), respectively. SRB 0 is used for RRC messages which use the CCCH, SRB 1 is for RRC messages using DCCH, and SRB 2 is for the (lower-priority) RRC messages using DCCH which only include dedicated non-access stratum (NAS) information. All RRC messages using DCCH are integrity-protected and ciphered by the PDCP layer (after security activation) and use ARQ protocols for reliable delivery through the RLC layer. The RRC messages using CCCH are not integrity protected and do not use ARQ in the RLC layer. It should also be noted that the NAS independently applies integrity protection and ciphering. The RLC supports data segmentation and concatenation [11]. Finally, the medium access control (MAC) sublayer [12] provides hybrid ARQ and is responsible for functionalities required for medium access, e.g., scheduling operation and random access. MAC also performs the mapping between logical channels and transport channels.
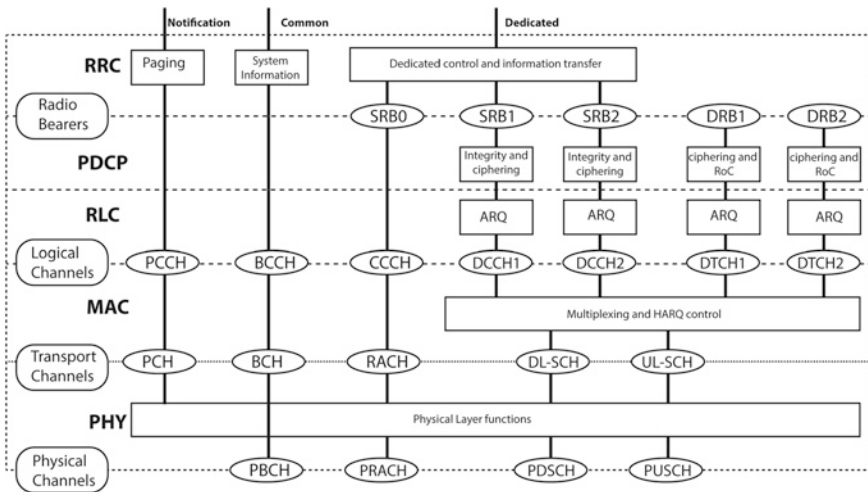

Fig. 2 Overall radio protocol architecture illustrating radio bearer mapping (adapted from [19])

2.3 Physical Layer

Basic concepts of physical layer are described in this subsection. More detailed description can be found in [4, 13].

2.3.1 Frame Structure

The transmitted LTE signal is organized in subframes of duration 1 ms, each consisting of 12 or 14 OFDM symbols, depending on whether normal or extended CP is used. Ten subframes form a radio frame as shown in Fig. 3. The short subframe duration of 1 ms results in small delays, not only for user data, but also for control signaling such as the hybrid ARQ feedback and channel-quality feedback from UEs to eNodeBs.

The main difference between FDD and TDD is that in the latter special subframes provide the required guard time for downlink-to-uplink switching. Each special subframe is divided into three fields, namely the downlink part (DwPTS), the guard period (GP), and the uplink part (UpPTS) shown in the bottom of Fig. 3.

2.3.2 Downlink Air Interface

In the downlink, the LTE air interface uses orthogonal frequency-division multiple access (OFDMA) that is a multiple access technique based on OFDM. OFDMA enables the OFDM transmission to benefit from multiuser diversity, adaptive subcarrier assignment based on feedback information about frequency-selective channel conditions, considerably enhancing the total system spectral efficiency over single-user OFDM systems. OFDM is a technique that mitigates inter-symbol interference, exploits the scarce frequency resource nearly optimally, combines the advantages of broadband and narrowband transmission, while at the same time
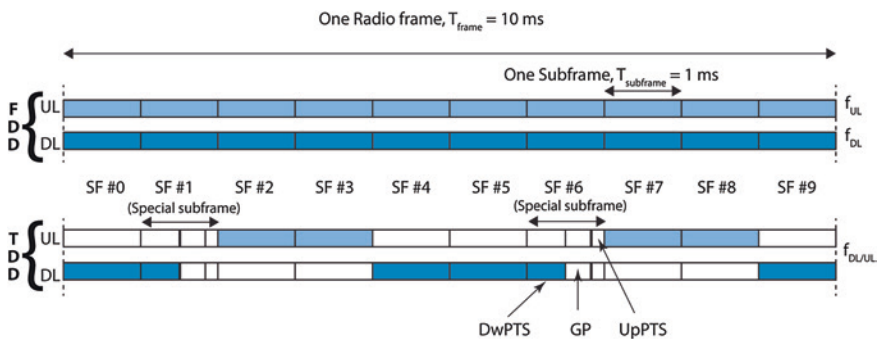

Fig. 3 LTE frame structure (adapted from [11])

avoids their disadvantages. OFDM avoids the guard band between the so-called subcarriers by a modulation of these subcarriers with rectangular pulses.

In the frequency domain, the spectrum of a pulse with duration T_{sym} corresponds to the $\mathrm{sinc}(x) = \sin(x)/x$ function with zero crossings at k/T_{sym}, $k = \ldots, -2, -1, 1, 2, \ldots$ Consequently, if these pulses modulate several subcarriers, the inter-subcarrier interference is zero with a subcarrier spacing of $1/T_{sym}$ that can be shown to be optimum according to the Nyquist theorem. Furthermore, this optimal value is reached without any filter. The modulation of the equally spaced subcarriers with rectangular pulses corresponds to an inverse discrete Fourier transform (DFT) in the time domain. At the receiver, the original symbols are reconstructed using the opposite function, namely the DFT.

In OFDM systems as LTE, the operation bandwidth can be easily adapted to the needs of the network operator. LTE FDD, for example, offers bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz with a subcarrier spacing of 15 kHz. The total bandwidth includes guard bands at both ends of the spectrum, so that 72, 180, 300, 600, 900, and 1200 subcarriers are conveyed in the respective bandwidth, as outlined in [14]. To support channel estimation for coherent demodulation, as well as for various measurement purposes, including not only measurements for mobility management but also channel-quality measurements, cell-specific reference signals (CRS) are transmitted in the downlink [15].

LTE uses other air interface technologies like MIMO, which is a technique that relies on multiple antennas at the transmitter and receiver to improve the system capacity [16]. LTE also uses code rates close to one when channel quality is excellent and complements this feature using link adaptation algorithms that allow the adjustment of channel quality by choosing the best modulation and coding scheme (MCS). Modulation schemes for quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) (16 and 64 points), which can be combined with multiple code rates, are also provided [17].

2.3.3 Downlink Physical Channels

Physical broadcast channel (PBCH) periodically broadcasts control parameters for initial cell access, such as downlink system bandwidth, the Physical Hybrid ARQ Indicator Channel structure, and the most significant 8 bits of the System Frame Number. These parameters encapsulated in a master information block, which is 14 bits long. PBCH is designed to be detectable without prior knowledge of the system bandwidth and robust enough to be recoverable at the cell edge. Each subframe is self-decodable, aiming at reducing latency and UE battery consumption in case of good signal quality. PBCH is transmitted using space frequency block code, a form of transmit diversity used in case of multiple antennas, thus contributing to increase cell coverage.

Physical downlink shared channel (PDSCH) is the main downlink data bearing channel, which is allocated to users on a dynamic and opportunistic basis. PDSCH carries data over transport blocks, which correspond to a MAC packet-data unit.

They are sent from the MAC layer to the PHY layer once per transmission time interval, which is 1 ms. In order to minimize propagation channel errors, convolutional turbo coder is used for forward error correction. Data is mapped to spatial layers according to the transmission modes in the multiple antenna schemes (e.g., spatial multiplexing, transmit diversity, etc.) and then mapped to a modulation symbol which includes QPSK, 16-QAM, and 64-QAM. PDSCH also conveys broadcast information not transmitted on the PBCH, comprising system information blocks and paging messages.

Physical downlink control channel (PDCCH) purpose is the transmission of the resource assignment for UEs, which are contained in a downlink control information message. Multiple PDCCHs can be transmitted in the same subframe using control channel elements, each of which is a set of four resource elements known as resource element groups. QPSK modulation is used, with four QPSK symbols per group. Furthermore, up to eight groups can be used per UE, depending on channel conditions, in order to increase robustness.

Physical control format indicator channel (PCFICH) is used for the control frame indicator transportation, which includes the number of OFDM symbols used for control channel transmission in each subframe (typically 1, 2, or 3). The 32-bit long CFI is mapped to 16 Resource Elements in the first OFDM symbol of each downlink frame using QPSK modulation.

Physical hybrid ARQ indicator channel (PHICH) is a control channel defined for the HARQ ACK/NAK signaling transmission, which indicates success status of uplink user data carried on PUSCH. BPSK modulation is defined for PHICH with a repetition factor of 3 to increase robustness.

2.3.4 Uplink Air Interface

In its uplink, the LTE standard employs a DFT-spread OFDM also denoted as single-carrier frequency-division multiple access (SC-FDMA). In comparison to conventional OFDM, this OFDM variant provides an improved peak-to-average power ratio (PAPR) that enables more power-efficient terminals [18]. In addition, it is possible to aggregate up to two streams by utilizing MIMO transmissions to increase the data rate.

Both frequency-selective and non-frequency-selective scheduling are supported in the uplink. In the former, the eNodeB exploits available channel knowledge to schedule a UE to transmit using specific physical resource blocks (PRBs) in the frequency domain where the channel response is good. In addition, to transmit data information, the uplink also conveys control information related to scheduling request [11], hybrid ARQ acknowledgments in response to downlink data packets, and channel-quality information for control signaling categorization. The amount of control information a UE can transmit in a subframe depends on the number of SC-FDMA symbols available for transmission of control signaling data [19]. More details about the LTE frame structure are given in the sequel.

2.3.5 Uplink Physical Channels

Physical uplink shared channel (PUSCH) carries user data, based on QPSK and 16-QAM schemes, with 64-QAM modulation being optional. Data bits are first channel-coded with a turbo code of rate of 1/3, followed by a rate matching process for a final code rate. Adjacent data symbols are mapped to adjacent SC-FDMA symbols in the time domain, and then across subcarriers. After this interleaving process, bits are scrambled and submitted to modulation mapping, DFT spreading, subcarrier mapping, and OFDM modulation. Besides user data, PUSCH conveys control signaling for information recovering in the uplink, such as transport format indicators and MIMO parameters. Control data is multiplexed with information data prior to DFT spreading.

Physical uplink control channel (PUCCH) is used for uplink transmission of control information, comprising Hybrid ARQ acknowledgments, channel-quality indicators, MIMO feedback (rank indicator and precoding matrix indicator), and scheduling requests. This channel transmits in a frequency region at the edge of the system bandwidth. It consists of one PRB per transmission, positioned at one channel edge, and another PRB at the opposite channel edge in the following slot, thus making use of frequency diversity.

Physical random access channel (PRACH) is an uplink channel primarily used for initial network access and short message transmission [20]. The main purpose of the random access procedure is to enable UEs to acquire uplink time synchronization and to access to the network. PRACH comprises a preamble composed of a cyclic prefix (CP), of length TCP, and a sequence part, of length T_{PRE}, as shown in Fig. 4.

Prime-length Zadoff–Chu sequences are adopted as random access preambles in LTE systems due to its constant amplitude zero autocorrelation properties [21–23], meaning that all points of the sequence lie on the unit circle and its autocorrelation is zero for all time shifts other than zero. These properties make Zadoff–Chu sequences very useful in channel estimation and time synchronization, and enable improved PRACH preamble detection performance [21].

It is worth mentioning that PRACH plays a key role in the cell coverage performance, since eNodeB must run detection algorithms in order to recover preambles transmitted by UEs, which requires complex statistical real-time processing in the uplink [22].

Fig. 4 Random access preamble format
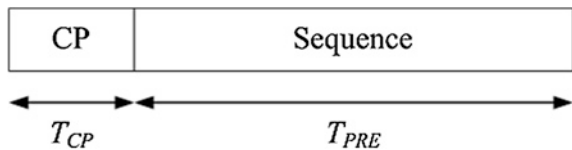
2.4 Other Important Features of LTE

Radio link conditions change in wireless system and there is a necessity to adapt the transmission and reception parameters to the actual link conditions. Therefore, a brief description of link adaptation and handover is presented in next lines.

2.4.1 Link Adaptation

LTE uses code rates close to 1 when the channel quality is excellent and complement this feature using link adaptation algorithms to allow the adjustment of channel quality by choosing the best MCS. LTE provides modulation schemes for QPSK, 16-QAM, and 64-QAM which can be combined with any code rate [17]. As an example, a mapping curve between signal-to-noise ratio (SNR) and MCS is shown in Fig. 5.

2.4.2 Handover

The handover procedure aims at maintaining UEs connections during the migration among neighboring cells. The goal is to minimize the impacts on the services
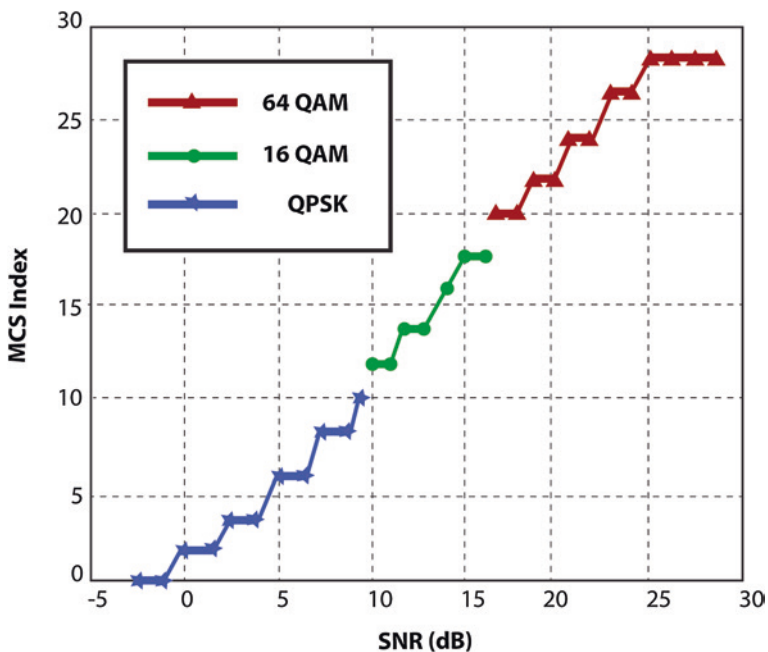

Fig. 5 Modulation and coding scheme (*MCS*) versus signal-to-noise ratio (*SNR*)

continuity, and a variety of mechanisms are defined by 3GPP in order to achieve it. The basic handover procedure mandated by 3GPP for LTE Rel. 8 [24] is illustrated in Fig. 6.

The handover procedure is based on a sequence of key events, detailed in Fig. 7, and starts with the measurement report of a handover event by the UE to its serving eNodeB. The UE periodically performs downlink radio channel measurements based on reference symbols, comprising received power and quality. Once a pre-configured threshold level is met, the UE sends the corresponding measurement report indicating the triggered event. In addition, the measurement report indicates the cell to which the UE has to be handed over, which is named "target" cell.

Based on the received measurement reports, the serving eNodeB starts handover process, with control signaling exchange with target eNodeB and admission control of the new UE. The communication between the serving and the target eNodeBs is performed over X2 interface. Upon successful handover setup, the decision is made and a handover command is sent to the UE. The connection between UE and the serving cell is released and then the UE attempts to
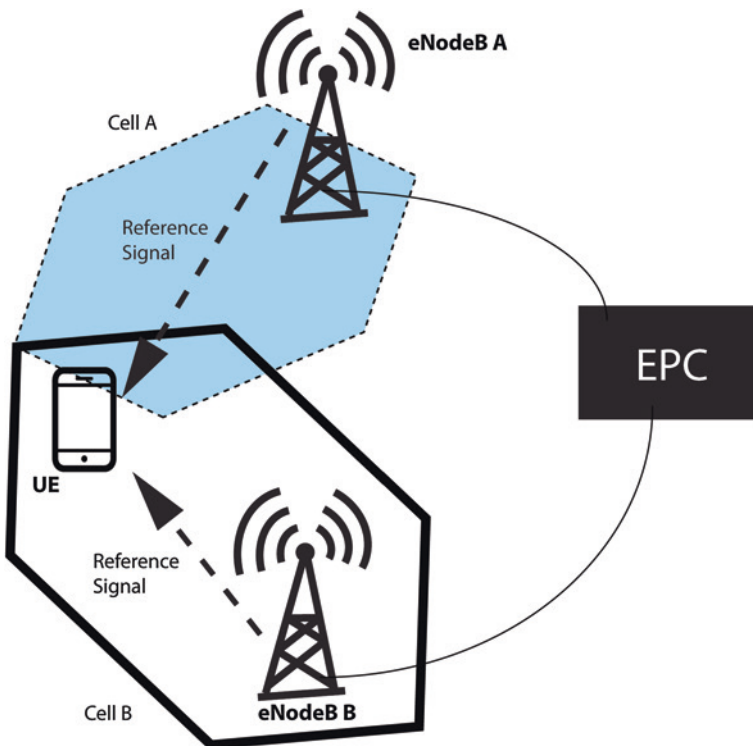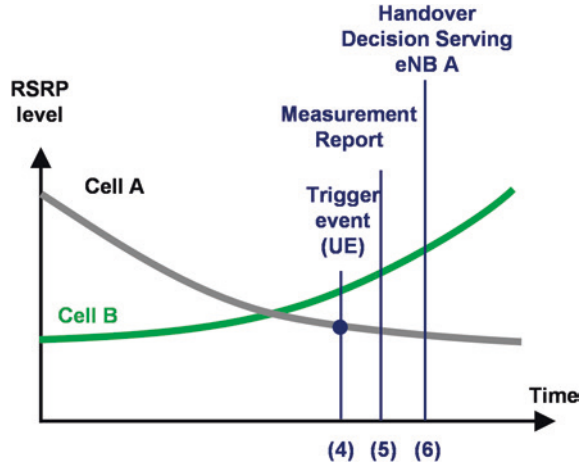

Fig. 6 Basic handover procedure used in LTE

Fig. 7 Handover triggering
events

synchronize and access the target eNodeB, by using the PRACH. Upon successful synchronization at the target eNodeB, this last one transmits an uplink scheduling grant to the UE. The UE responds with a handover confirm message, which notifies the completion of the handover procedure at the radio access network part.

3 Advanced Features

Having the basic LTE infrastructure and features discussed in Sect. 2, this section now describes what we shall refer to as advanced features. Such functionalities have been introduced and further developed throughout subsequent LTE releases bearing in mind three goals that are regarded as main requirements for next-generation mobile networks: better spectrum usage (whether by exploiting new bands or improving spectral efficiency), network densification, and performance improvements. This latter requirement will focus solely on features related to interference management, as other improvements, such as air interface modifications for latency reduction in the physical layer and coordinated multipoint, are out of the scope of this chapter.

3.1 Spectrum Usage, Spectrum Efficiency and Capacity

3.1.1 LTE/Wi-Fi Interworking

Mobile operators are known to prioritize the delivery of advanced services and user experience over licensed frequency bands, and this will remain so according

Fig. 8 A typical scenario of licensed-assisted access operating in licensed and unlicensed bands
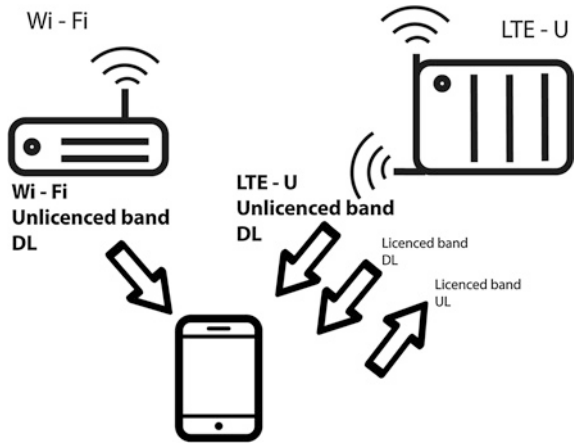
to a recent assessment from 3GPP [9]. Notwithstanding the unquestionable role played by the licensed spectrum in the quest for more bandwidth, opportunistic use of unlicensed spectrum has been receiving increased attention as complementary means to meet the ever-growing traffic demands. One way to benefit from unlicensed spectrum is through LTE/Wi-Fi Interworking, a framework for traffic offload that is under development since LTE Rel. 8. Interworking forms are getting tighter and tighter throughout subsequent LTE releases, and proposals for Rel. 13 include LTE/Wi-Fi aggregation, mobility control based on UE measurements and network steering capabilities, and an interface to interconnect eNodeBs with Wi-Fi access points [25].

Licensed-assisted access (LAA), sometimes referred to as LTE Unlicensed, is a term used within 3GPP to denote a study item aimed to look into alternative interworking ways for enhancing the operation of LTE in unlicensed bands. The underlying idea of LAA consists of aggregating a primary cell (PCell) with a secondary cell (SCell), respectively, operating in licensed and unlicensed spectra, as it is shown in Fig. 8. The goal of the PCell is to deliver critical information and ascertain the quality of service, whereas that of the SCell is to boost data rates in an opportunistic fashion. The SCell can be set up as downlink-only or both uplink and downlink, although a common view at 3GPP is that the study will begin with the first option and follow with the second one in the future [9]. The core technology under development for LAA targets to be as much frequency agnostic as possible, so initial emphasis will be on unlicensed operation in the 5 GHz bands with other frequencies addressed at later stage.

LAA raises some specific issues that will need to be dealt with, namely effective and "fair"[1] coexistence with Wi-Fi and effective and fair coexistence among

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[1]By "fair" it is meant that LAA should not impact Wi-Fi services (data, video, and voice services) more than an additional Wi-Fi network operating on the same carrier would. These metrics could include throughput, latency, and jitter, but will be exactly defined in the coexistence study.

LAA networks operated by different operators. The use of coexistence mechanisms has been deemed required for this to work, including clear channel assessment, discontinuous transmission on carrier with limited maximum transmission duration, dynamic frequency selection in certain bands/regions, carrier selection, and transmit power control [25]. Preliminary simulation results suggest that LTE augmented with appropriate coexistence mechanisms for unlicensed spectrum can effectively coexist with Wi-Fi, and is able to outperform it in terms of spectral efficiency.

3.1.2 Carrier Aggregation

Perhaps the most straightforward way to increase capacity is by making more bandwidth available to a communications system. Since LTE Rel. 10, this is done by simply aggregating more bandwidth through carrier aggregation (CA). Backward compatibility is a mandatory characteristic of the CA technology. Therefore, during the standardization of LTE-Advanced features, 3GPP determined that CA would have to keep backward compatibility with UEs based on Releases 8 and 9. So the larger bandwidths introduced with LTE Rel. 10 are provided through aggregation of standard LTE Rel. 8 and 9 carriers. Other important characteristic of CA, which renders it one of the most remarkable contributions of Rel. 10, is that it can be used for both FDD and TDD deployments of LTE-Advanced systems [26].

CA works with contiguous and non-contiguous spectrum. Each aggregated carrier denotes a component carrier (CC). Each CC can have one of the standardized bandwidths: 1.4, 3, 5, 10, 15, or 20 MHz. A maximum of up to five CCs can be aggregated; hence, the maximum aggregated bandwidth is 100 MHz. As illustrated in Fig. 9, the individual bandwidth of each CC adding up to the aggregated system bandwidth can be different. The number of aggregated carriers can be different in the downlink and uplink for FDD systems. However, the number of uplink CCs must always be lower than or equal to the number of downlink CCs. On the other
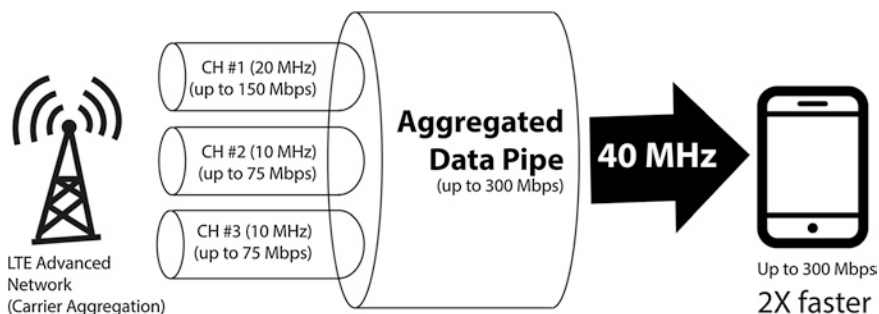

Fig. 9 Exemplary realization of CA where three CCs with individual bandwidths of 20, 10, and 10 MHz are aggregated to yield a wider 40 MHz system bandwidth

hand, for TDD systems, both the number of CCs and their individual bandwidths will be equal for both downlink and uplink [27].

Ongoing work within the scope of LTE Rel. 13 seeks to address the operators' need to expand the CA framework so that it is able to aggregate more than five CCs. The goal is to further boost achievable data rates by aggregating more than five CCs (at least in the downlink). Flexibility will also undergo a major improvement, as the resulting system will be capable of aggregating larger numbers of carriers in different frequency bands. Such enhanced CA framework is also of utmost importance in LAA, explained earlier in this section. However, not all the aspects of CA scale directly with an increased CC number and a number of issues arise when more than three CCs are used [28]:

- PUCCH transmission currently is applied only in the PCell, so increasing the number of CCs will increase the PUCCH payload size per CA UE. Besides the impact on the PCell uplink, which gets worse as the number of CA UEs grows, having all PUCCH transmissions managed by the PCell is believed to impact performance. PCell overload can be alleviated by distributing the UEs PUCCH resources in the network, although this comes at the expense of more involved installation, i.e., simple small cell installation with remote radio heads is no longer possible;
- The dual connectivity concept developed within the scope of LTE Rel. 12 requires UEs capable of uplink CA with simultaneous PUCCH/PUCCH and PUCCH/PUSCH transmissions across cell groups. The introduction of PUCCH in the SCell, known as Dual PUCCH, is seen as essential as it can ease the aforementioned burdens thus allowing for an increased number of aggregated carriers in the downlink. This idea, however, was dropped from the corresponding work item objective due to the tight schedule of LTE Rel-12;
- Finally, and independent of Dual PUCCH mechanisms, CA extension to support up to 32 CCs requires enhancements also when it comes to hybrid ARQ acknowledgment feedback and channel state information feedback carried on a single uplink carrier. This has potential to improve CA in the case of TDD PCells, which faces limitations on PDSCH hybrid ARQ acknowledgment feedback already with three CCs.

3.1.3 Advanced MIMO Techniques

The last relevant features of LTE Rel. 13 discussed in this chapter are elevation beamforming and full-dimension MIMO. In this context, 3GPP seeks a better understanding on how two-dimensional antenna arrays can further improve the spectral efficiency of LTE by exploiting the vertical dimension in addition to the azimuth dimension (the latter has been exploited in isolation since LTE Rel. 10) for beamforming and MIMO operations. A number of strategies are enabled if additional control over the elevation dimension is available, e.g., vertical pattern beamwidth and/or downtilt can be controlled in an adaptive fashion, vertical

domain sectorization, and user-specific elevation beamforming. Besides being a standard-transparent technology, this can improve the average system performance. Elevation beamforming, in contrast, is a UE-specific technique with potential to increase the signal to interference and noise ratio statistics seen by the UEs. This is possible by pointing the vertical antenna pattern in the direction of the intended UE, thus generating less interference to other non-intended UEs operating in adjacent sectors.

The study [28], which is split into two phases, aims to determine the performance benefit of enhancements targeting the operation of two-dimensional antenna arrays (including a single column of cross-poles) with eight or more transceiver units, each having its own, independent amplitude and phase control. Phase 1 will take into account the three-dimensional channel model proposed in [29] to identify antenna settings for two-dimensional arrays with up to 64 antenna ports at the eNodeB, and to evaluate the performance of LTE Rel. 12 downlink MIMO for both single- and multiuser cases. Phase 2 comprises the evaluation of potential enhancements in reference signal design, codebook, and feedback mechanisms for single-user and multiuser MIMO transmission schemes (including support for higher dimension multiuser MIMO settings), channel reciprocity based operation, diversity transmission schemes, methods for common channel coverage, cell/point selection, and/or RRM measurement reliability.

3.2 Network Densification

3GPP began work toward the standardization of self-optimizing and self-organizing capabilities in LTE Releases 8 and 9. These standards provide network intelligence and management features that automate the configuration and optimization of wireless networks as a response to variations in the actual radio channel conditions. A key goal of 3GPP has been the ability to support self-organizing networks (SON) features in multivendor environments, so a significant part of this standardization work has been devoted to defining the appropriate interfaces to allow exchange of common information that can then be used by different SON algorithms [30]. SON specifications have been built over the existing 3GPP network management architecture.

In LTE Rel. 8, the functionality focuses on procedures associated with initial equipment installation and integration to support the commercial deployment of the first LTE networks, also known as "eNodeB self-configuration". Such procedures include:

- Automatic inventory;
- Automatic software download [31];
- Automatic neighbor relation [32];
- Automatic physical cell ID assignment [33].

In LTE Rel. 9, the SON functionality focuses on operational aspects of commercial networks, particularly on key aspects related to network optimization procedures. The standardization scope includes the following additional use cases [30, 34]:

- Mobility robustness/handover optimization (MRO): in particular, the handover parameter optimization function shall aim at reducing the number of handover-related failures that cause degradation in user experience, such as call drops, radio link failures during or shortly after handovers, and reduced data rates;
- Random access channel (RACH) optimization: an automatic RACH optimization function monitors the prevailing conditions, e.g., a change on RACH load, uplink interference, and determines and updates the appropriate parameters;
- Load balancing optimization: each scenario shall include the load balancing on intra-frequency, inter-frequency, and inter-RAT;
- Inter-cell interference coordination (ICIC): the following scenarios shall be considered in interference control: uplink ICIC, and downlink ICIC;
- Capacity and coverage optimization, in this use case operator shall be able to configure the objectives and targets for the coverage and capacity optimization function.

Other SON-related aspects discussed within the scope of LTE Rel. 9 framework include improvement of the telecom management system so as to increase energy savings, new operations, administration, and maintenance interface to control home eNodeBs, UE reporting functionality to minimize the amount of drive tests, studies on self-testing and self- healing functions, and minimization of drive testing. As will be seen later on in this chapter, SON-related functions continued to expand through the subsequent releases of the LTE standard [35].

In order to maintain network quality with minimum manual intervention on the part of the operator, the concept of SON has been advanced within the scope of the LTE standard since its introduction in Rel. 8. The need for enhanced SON procedures was one of the goals of LTE Rel. 11, as 3GPP identified that previous releases had issues with respect to mobility and inter-RAT operation. The resulting procedures for enhanced SON are found in [36] and encompass:

- MRO test cases were completed in LTE Rel. 10, so that networks based on that release are capable of detecting related issues whenever the UE reconnects to an LTE cell. The event whereby a cell at a different RAT may mistakenly be selected after connection failure was not addressed (no mechanism is currently available to detect nor to correct it). Inter-RAT failure issues related to the deployment of LTE over 2G/3G coverage and connection failure resolution support for some heterogeneous networks (HetNets) deployments were dealt with in LTE Rel. 11;
- Some problems related to mobility were identified since LTE Rel. 9 and have been addressed in LTE Rel. 11. Inter-RAT "ping-pongs", for instance, are known not to result in a failure but are rather inefficient in that they create unnecessary signaling. Therefore, it was found relevant to exploit UE history data to enhance the existing LTE Rel. 8 mechanism.

3.3 Interference Management

3.3.1 Inter-Cell Interference Coordination

One limiting aspect of system throughput performance in cellular networks is
inter-cell interference, especially in the case of cell-edge users. A simple method
to improve cell-edge data rates is to statically restrict the use of certain parts of the
operation bandwidth. Such static schemes fall into one of three broad categories:
traditional (hard) fractional frequency reuse [37], soft frequency reuse [38], and
partial frequency reuse [39]. 3GPP addressed this issue through an eNodeB sched-
uling strategy that includes an ICIC element. This early ICIC mitigates interfer-
ence on traffic channels only, and operates in both power and frequency domains
to mitigate cell-edge interference coming from neighboring cells. Time-domain
interference coordination is not used, as it would interfere with the operation of
hybrid ARQ processes (especially in the uplink where synchronous hybrid ARQ is
used) [40]. In LTE Rel. 8, ICIC is inherently a multicell RRM function that needs
to take into account information from multiple cells, e.g., the resource usage sta-
tus and traffic load situation. The preferred ICIC method may be different in the
uplink and downlink [41].

The coordination between LTE cell sites is achieved by exchanging messages
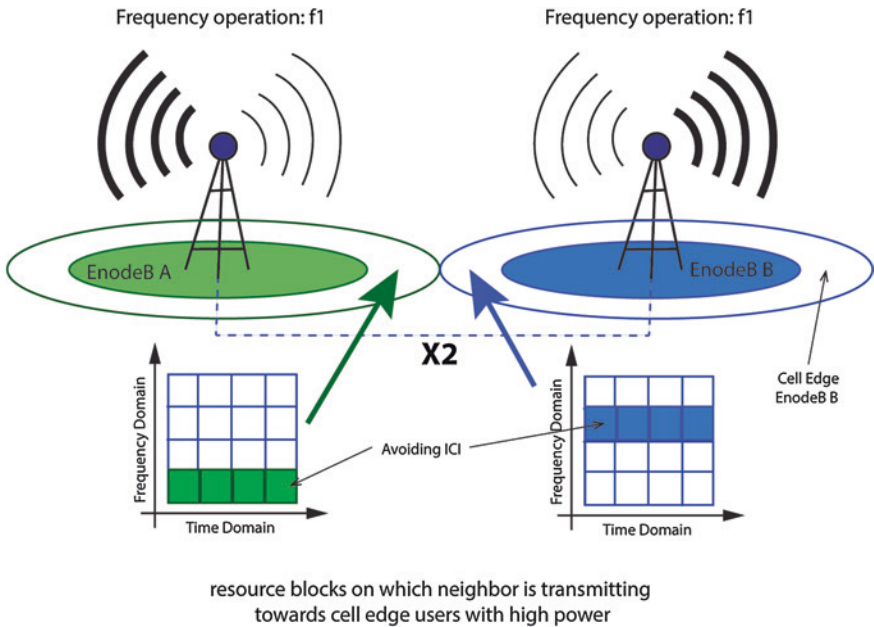between eNodeBs over the X2 interface as shown in Fig. 10. Frequency-domain

Fig. 10 Pictorial description of the ICIC strategy mandated within the LTE Rel. 8 standard

ICIC in the downlink basically controls the cell power for resources by sending a relative narrowband transmit power message as often as every 200 ms. Such messages contain information about whether a given PRB is limited by transmit power. When a neighboring eNodeB listens to this message, it can avoid scheduling on the indicated PRB. Two messages are defined for uplink interference coordination, namely high interference indicator (HII) and overload indication, and exchanged between eNodeBs as often as every 20 ms. HII is used to communicate on which PRB the eNodeB is going to schedule cell-edge users. By listening to this message, a neighboring eNodeB can avoid scheduling cell-edge users in that same indicated PRB. This results in reduced uplink interference for both cells. The action taken by an eNodeB when it receives an HII message is implementation specific. An eNodeB sends an overload indication to indicate the level of interference (low, mid, or high) experienced in different PRBs to neighboring eNodeBs. Upon receiving such a message, an eNodeB can change its scheduling pattern to free the PRBs indicated in that message, thus reducing the interference for cell-edge users.

We have seen that basic ICIC technology has been in use since LTE Rel. 8. However, in the case of HetNets, where macro cells are complemented with small cells, i.e., femtocells, picocells, and microcells, the interference imposed by small cells on the macro cell and vice versa still lacked a proper strategy. This issue was properly dealt with in LTE Rel. 10 with the introduction of an enhanced ICIC (eICIC) feature, designed bearing the aforementioned interference issues common in HetNets.

eICIC relies on power, frequency, and time domain strategies to mitigate intra-frequency interference. Power and frequency strategies in LTE Rel. 10 are the same for LTE Rel. 8. The strategy used to reduce interference in the time domain is that a serving cell stops transmitting or transmits with very low power at a certain subframe, so that an interfering cell can transmit its signal during that period. The subframe with very low signal power is termed almost blank subframe (ABS). ABSs do not comprise any traffic channels and are mostly control channel frames with very low power. If a macro cell configures ABSs, UEs connected to small cells should then send their data during such subframes, avoiding interference from the macro cell. Therefore, and in contrast to the baseline ICIC, eICIC not only mitigates interference on traffic channels but also on control channels [42].

eICIC strategies proposed in LTE Rel. 10 are, however, not able to address interference caused by CRS transmitted to support legacy deployments, i.e., LTE networks based on Releases 8 and 9. CRS and other mandatory system information are the only signals transmitted during ABS, and it is employed for mobility measurements and demodulation of the downlink control and data channels. Therefore, interference caused by neighboring cells could be detrimental for the measurement of channel quality and demodulation of various data and control channels [43].

In this context, the main enhancement introduced in LTE Rel. 11 is the provision of CRS assistance information of aggressor cells to the UEs. CRS assistance information is provided by the eNodeB to cancel unwanted CRS, thus mitigating

further interference. This information helps UEs improve both CRS-based measurements and demodulation of data/control channels by indicating them the neighbor cells that have ABS configured. This improvement is known as further enhanced ICIC (feICIC). Not only is this technology able to tackle the interference scenarios described from Releases 8 through 10 but it also manages CRS-based interference through coordinated transmitter and receiver actions [44].

As with eICIC, feICIC was also conceived to deal with interference issues in HetNets. The idea is to add a layer of complexity to the receivers, which now must also handle inter-cell interference cancellation. One important benefit introduced thereby is that the mitigation of neighbor CRS interference enables further cell range extension and ensures that weak cells can be detected [45].

3.3.2 Interference Rejection Combining

The LTE technology provides high spectral efficiency within one cell, but it can be shown to be highly vulnerable to inter-cell interference. Interference rejection combining (IRC) is a technology introduced in LTE Rel. 11, which is implemented in the layer 1 of LTE systems, and can be described as an efficient alternative to increase uplink bit rates in areas where cells overlap [46]. Interference caused by adjacent cells restricts throughput in environments where the power of the interference signal is stronger than that of the noise.

The use of IRC receiver technology at the UE was advanced as means to reject and suppress interference, thus mitigating the effects of unwanted signals and increasing user throughput [47]. The main idea behind IRC is the regeneration of the transmitted signal based on the estimation of data from previous receptions, emulation of the distortion introduced by the multipath channels and, finally, the subtraction of all regenerated interfering signals from the uplink received signals in order to obtain a more reliable estimation of the original users' data.

This feature uses the spatial separation and characteristics of inter-cell interference to determine the power of the interfering UE which belongs to another cell. Once the pattern and power level is determined, the victim cell can then remove the interferer from the received signals [48].

4 Advanced Services

This section deals with two services that have been receiving special attention within 3GPP, namely multimedia broadcasting services and machine-centered communication services. The former provides operators with an economical solution for multiuser, high-bandwidth services, while the latter seeks to leverage the LTE technology as competitive option for the multibillion Internet of Things market.

4.1 Multimedia Broadcasting and Multicasting

The term multimedia broadcast and multicast service (MBMS) is not fundamentally new to 3GPP, and so not defined as an LTE-only feature. In fact, this feature was first specified in 3GPP Rel. 6 with the goal of making it possible for network operators to broadcast over their cellular networks. MBMS provides native support for broad- and multi-casting IP packets in wireless networks, thus allowing high bandwidth services to be offered to multiple users in an economical manner, e.g., on-demand video, mobile TV, short news clips, weather reports, match results, and software updates [49]. The evolved MBMS (eMBMS) framework has as its key motivation the integration of broadcast and multicast extensions into mobile communication systems, thus enabling efficient group-related data distribution services—especially over the radio interface. As defined in LTE Releases 8 and 9 [50, 51], eMBMS baseline definition supports adaptive hypertext transfer protocol streaming via broadcast, and a few bugs have been identified and fixed through real implementation.

eMBMS is a unidirectional service, which targets the delivery of multimedia data from a single source entity to multiple recipients, optimizing the use of scarce resources. The main requirements during provisioning of eMBMS services are ensuring efficient overall usage of radio and network resources and reducing the power requirements for the provisioning of such demanding services [52]. Multimedia broadcast single frequency network (MBSFN) operation is a key new feature of LTE that brings about the possibility of exploiting the OFDM radio interface to transmit broadcast or multicast data as a multicell transmission over a synchronized SFN. A pictorial description of the eMBMS service deployed in MBSFN operation is given in Fig. 11.

MBSFN transmission enables a more efficient operation of the MBMS service, allowing over-the-air combination of multicell transmissions toward the UEs. In
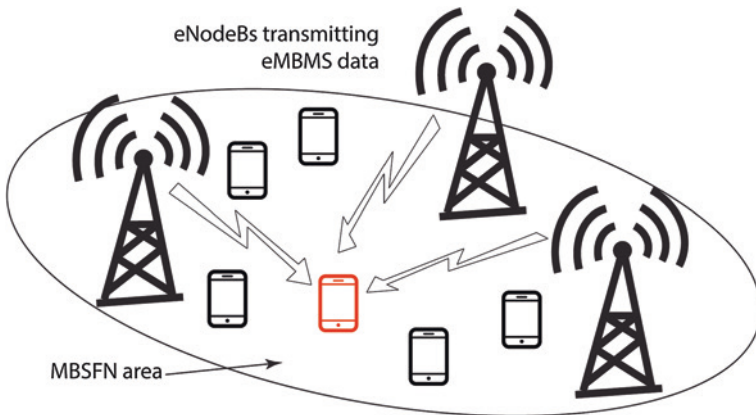

Fig. 11 Pictorial description of the eMBMS service in MBSFN operation

an MBSFN operation, MBMS data is transmitted simultaneously over the air from multiple tightly time-synchronized cells. A UE receiver will therefore observe multiple versions of the signal with different delays due to the multicell transmission. There will be no inter-symbol interference, provided that transmissions from multiple cells are sufficiently synchronized for each to arrive at the UE within the CP at the start of the symbol. In effect, this makes the MBSFN transmission appear to a UE as a transmission from a single large cell, so the UE receiver can treat multicell transmissions in the same way as multipath components of a single-cell transmission without incurring any additional complexity [53–56].

4.2 Machine-Type Communications

Machine-type communications (MTC) have been regarded as such a revenue generation opportunity that mobile operators would not want to let it slide. From the operator perspective, it is clearly more efficient if future MTC devices can be served using already deployed RATs. One crucial question that remains open thus far is whether LTE technology can be competitive enough when it comes to efficient MTC support. MTC devices, often referred to as MTC UEs in the context of LTE, will likely be deployed in large numbers, so individual device cost plays a role of utmost importance for leveraging future LTE-based MTC networks. In such networks, communication will take place in the form of infrequent, short burst transmissions, which in turn call for low operational power consumption on the part of MTC UEs.

Aware of this promising Internet of Things market, 3GPP plans to enhance LTE suitability for MTC-specific applications. Standardization efforts began in Rel. 12 [57] and are expected to continue in Rel. 13 [58]. The goal is to introduce a new, low-complex UE category able to operate with bandwidth and transmit power requirements both reduced for ultra-long battery life. Operation channels 1.4 MHz wide are envisioned, so operators can multiplex reduced bandwidth MTC UEs and regular UEs in their existing LTE deployments. To cater to operation in the presence of poor propagation conditions, e.g., in case of geotechnical sensors deployed under the ground level, delay-tolerant MTC UEs will have a coverage improvement of the order of 15–20 dB.

Assuming multislot class 2 terminals based on enhanced general packet radio service as benchmark for cost comparison and minimum data rate capability, the 3GPP study has put together a list of features and their modifications to reduce cost and improve coverage along with various hardware simplifications. It turns out that the three actions yielding the largest UE cost reduction gains are [57]:

- Reduced bandwidth for both RF and baseband for downlink and uplink: Gain of 39 % at the expense of 1–3 dB degradation to cell coverage;
- Single receive RF: Gains of up to 29 % at the cost of 4 dB degradation to cell coverage;
- Peak rate reduction: Gains of up to 21 % without any degradation to cell coverage.

When jointly implemented, the actions above can cut off UE costs in as much as 59 %. The resulting degradation to cell coverage was found to lie in the range 5–9 dB in this case. Other actions assessed in the study include half-duplex FDD, uplink transmit power reduction, and transmission mode reduction.

5 Concluding Remarks

This brief chapter has presented a comprehensive overview of current LTE systems and beyond. We have presented the baseline technology and the underlying features of network architecture, protocols, and air interface introduced in the first LTE release back in 2008. Having the basics put in place, we moved forward to discuss advanced features introduced and further developed throughout subsequent LTE releases. The discussion found in the present chapter takes into consideration even the still under discussion LTE Release 13, which has in March 2016 its estimated freeze date.

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