CHAPTER

LTE RADIO ACCESS: AN OVERVIEW

3

The work on LTE was initiated in late 2004 with the overall aim of providing a new radio-access technology focusing on packet-switched data only. The first phase of the 3GPP work on LTE was to define a set of performance and capability targets for LTE [6]. This included targets on peak data rates, user/system throughput, spectral efficiency, and control/user-plane latency. In addition, requirements were also set on spectrum flexibility, as well as on interaction/compatibility with other 3GPP radio-access technologies (GSM, WCDMA/HSPA, and TD-SCDMA).

Once the targets were set, 3GPP studies on the feasibility of different technical solutions considered for LTE were followed by development of detailed specifications. The first release of the LTE specifications, release 8, was completed in 2008 and commercial network operation began in late 2009. Release 8 has been followed by additional LTE releases, introducing additional functionality and capabilities in different areas, as illustrated in Figure 3.1. Of particular interest are release 10, being the first release of LTE-Advanced, and release 13, finalized late 2015 and the first release of LTE-Advanced Pro. Currently, as of this writing, 3GPP is working on LTE release 14.

In parallel to the development of LTE, there has also been an evolution of the overall 3GPP network architecture, termed *system architecture evolution* (SAE), including both the radio-access network and the core network. Requirements were also set on the architecture evolution, leading to a new flat radio-access-network architecture with a single type of node, the *eNodeB*,[1] as well as a new core-network architecture. An excellent description of the LTE-associated core-network architecture, the *evolved packet core* (EPC), can be found in [5].

The remaining part of this chapter provides an overview of LTE. The most important technology components of LTE release 8—including transmission schemes, scheduling, multi-antenna support, and spectrum flexibility—are presented, as well as the additional features and enhancements introduced in later releases up to and including release 13. The chapter can either be read on its own to get a high-level overview of LTE, or as an introduction to the subsequent chapters.

[1]eNodeB is a 3GPP term that can roughly be seen as being equivalent to a base station, see further Chapter 4.

4G, LTE-Advanced Pro and The Road to 5G. http://dx.doi.org/10.1016/B978-0-12-804575-6.00003-0

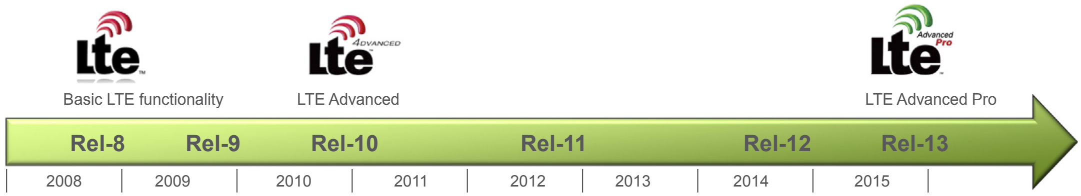

FIGURE 3.1

LTE and its evolution.

The following chapters, Chapters 4–22, provide a detailed description of the LTE radio-access technology. Chapter 4 provides an overview of the LTE protocol structure, including RLC, MAC, and the physical layer, explaining the logical and physical channels, and the related data flow. The time–frequency structure on which LTE is based is covered in Chapter 5, together with a brief overview of the LTE antenna-port concept. This is followed by a detailed description of the LTE physical-layer functionality for downlink and uplink transmission in Chapters 6 and 7, respectively. Chapter 8 contains a description of LTE retransmission mechanisms, followed by a discussion on the mechanisms available in LTE to support advanced scheduling and link adaptation in Chapter 9. Channel-state reporting to support scheduling, including handling of large antenna arrays, is covered in Chapter 10. Access procedures, necessary for a device (or a terminal, in 3GPP known as a *user equipment*, UE) to connect to the network, are the topic of Chapter 11.

The following chapters focus on some of the enhancements incorporated into LTE from release 10 onwards, starting with carrier aggregation (CA) in Chapter 12. Multi-point coordination/transmission is discussed in Chapter 13, followed by a discussion of heterogeneous deployments based on LTE in Chapter 14. Chapter 15 covers small-cell enhancements and dynamic TDD, Chapter 16 dual connectivity, and Chapter 17 operation in unlicensed spectrum. Relaying and broadcast/multicast are the topics of Chapters 18 and 19, respectively. Chapter 20 describes enhancements for improved support of machine-type communication while Chapter 21 focuses on direct device-to-device communication. The LTE part of the book is concluded with a discussion on the definition of radio-frequency (RF) requirements, taking into account the spectrum flexibility.

Finally, Chapters 23 and 24 provide an overview of the new 5G radio-access technology currently under discussion in 3GPP and Chapter 25 concludes the discussion on 5G radio access.

3.1 LTE BASIC TECHNOLOGIES

Release 8 is the first LTE release and forms the basis for the following releases. Due to time limitations for the release 8 work, some smaller features originally planned for release 8 was postponed for release 9, which thus can be seen as part of the basic LTE framework. In the following sections, the basic LTE technologies in release 8/9 are described.

3.1.1 TRANSMISSION SCHEME

The LTE downlink transmission scheme is based on conventional *orthogonal frequency-division multiplexing* (OFDM) [53], an attractive transmission scheme for several reasons. Due to the relatively long OFDM symbol time in combination with a cyclic prefix, OFDM provides a high degree of robustness against channel-frequency selectivity. Although signal corruption due to a frequency-selective channel can, in principle, be handled by equalization at the receiver side, the complexity of such equalization starts to become unattractively high for implementation in a device at larger bandwidths and especially in combination with advanced multi-antenna transmission schemes such as spatial multiplexing. Therefore, OFDM is an attractive choice for LTE for which a wide bandwidth and support for advanced multi-antenna transmission were key requirements.

OFDM also provides some additional benefits relevant for LTE:

- OFDM provides access to the frequency domain, thereby enabling an additional degree of freedom to the channel-dependent scheduler compared to time-domain-only scheduling used in major 3G systems.
- Flexible transmission bandwidth to support operation in spectrum allocations of different sizes is straightforward with OFDM, at least from a baseband perspective, by varying the number of OFDM subcarriers used for transmission. Note, however, that support of a flexible transmission bandwidth also requires flexible RF filtering, and so on, for which the exact transmission scheme is to a large extent irrelevant. Nevertheless, maintaining the same baseband-processing structure, regardless of the bandwidth, eases device development and implementation.
- Broadcast/multicast transmission, where the same information is transmitted from multiple base stations, is straightforward with OFDM as described in Chapter 19.

The LTE uplink is also based on OFDM transmission. However, to enable high-power amplifier efficiency on the device side, different means are taken to reduce the *cubic metric* [10] of uplink transmissions. Cubic metric is a measure of the amount of additional back-off needed for a certain signal waveform, relative to the back-off needed for some reference waveform. It captures similar properties as the more commonly known peak-to-average ratio but better represents the actual back-off needed in an implementation. Low cubic metric is achieved by preceding the OFDM modulator by a DFT precoder, leading to *DFT-spread OFDM* (DFTS-OFDM), see Chapter 7. Often the term DFTS-OFDM is used to describe the LTE uplink transmission scheme in general. However, it should be understood that DFTS-OFDM is only used for uplink data transmission. As described in more detail in later chapters, other means are used to achieve a low cubic metric for other types of uplink transmissions. Thus, the LTE uplink transmission scheme should be described as OFDM with different techniques, including DFT precoding for data transmission, being used to reduce the cubic metric of the transmitted signal.

The use of OFDM-based transmission for the LTE uplink allows for orthogonal separation of uplink transmissions also in the frequency domain. Orthogonal separation is in many cases beneficial as it avoids interference between uplink transmissions from different devices within the cell (*intra-cell interference*). Allocating a very large instantaneous bandwidth for transmission from a single device is not an efficient strategy in situations where the data rate is mainly limited by the available device transmit power rather than the bandwidth. In such situations a device can instead be allocated only a part of the total available bandwidth and other devices within the cell can be scheduled to transmit in parallel on the remaining part of the spectrum. In other words, the LTE uplink transmission scheme allows for both *time-division multiple access* (TDMA) and *frequency-division multiple access* (FDMA) to separate users.

3.1.2 CHANNEL-DEPENDENT SCHEDULING AND RATE ADAPTATION

One key characteristic of mobile radio communication is the large and typically rapid variations in the instantaneous channel conditions stemming from frequency-selective fading, distance-dependent path loss, and random interference variations due to transmissions in other cells and by other terminals. Instead trying to combat these variations through, for example, power control, LTE tries to exploit these variations through *channel-dependent scheduling* where the time—frequency resources are dynamically shared between users. Dynamic sharing of resources across the users is well matched to the rapidly varying resource requirements posed by packet-data communication and also enables several of the other key technologies on which LTE is based.

The scheduler controls, for each time instant, to which users the different parts of the shared resource should be assigned and the data rate to be used for each transmission. Thus, *rate adaptation* (i.e., trying to dynamically adjust the data rate to match the instantaneous channel conditions) can be seen as a part of the scheduling functionality.

However, even if the rate adaptation successfully selects an appropriate data rate, there is a certain likelihood of transmission errors. To handle transmission errors, *fast hybrid-ARQ with soft combining* is used in LTE to allow the device to rapidly request retransmissions of erroneously received data blocks and to provide a tool for implicit rate adaptation. Retransmissions can be rapidly requested after each packet transmission, thereby minimizing the impact on end-user performance from erroneously received packets. Incremental redundancy is used as the soft combining strategy, and the receiver buffers the soft bits to be able to perform soft combining between transmission attempts.

The scheduler is a key element and to a large extent determines the overall system performance, especially in a highly loaded network. Both downlink and uplink transmissions are subject to tight scheduling in LTE. A substantial gain in system capacity can be achieved if the channel conditions are taken into account in the scheduling decision, so-called *channel-dependent scheduling*, where transmission are directed to user with momentarily favorable channel conditions. Due to the use of OFDM in both the downlink and uplink transmission directions, the scheduler has access to both the time and frequency domains. In other words, the scheduler can, for each time instant and frequency region, select the user with the best channel conditions, as illustrated in Figure 3.2.

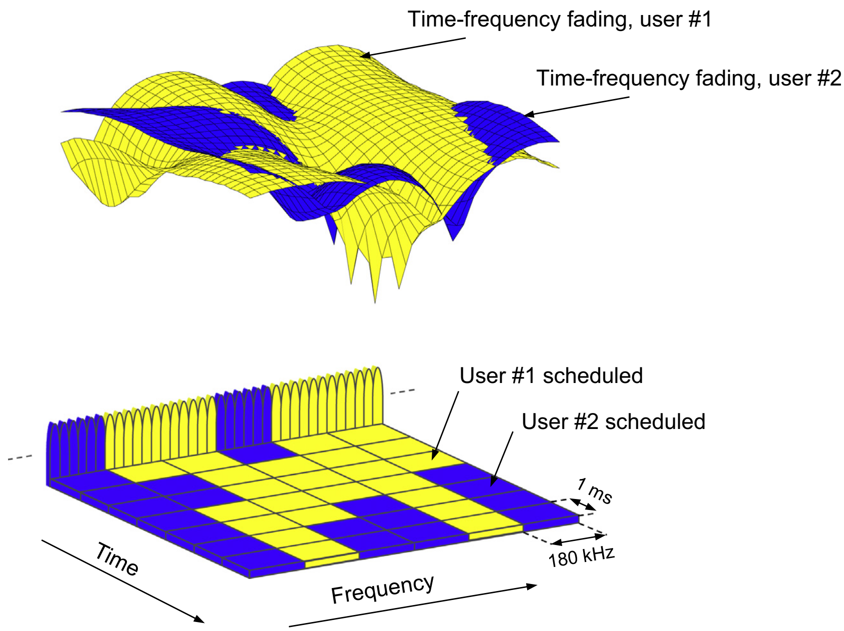

FIGURE 3.2

Downlink channel-dependent scheduling in time and frequency domains.

The possibility of channel-dependent scheduling in the frequency domain is particularly useful at low device speeds—in other words, when the channel is varying slowly in time. Channel-dependent scheduling relies on channel-quality variations between users to obtain a gain in system capacity. For delay-sensitive services, a time-domain-only scheduler may, due to the delay constraints, be forced to schedule a particular user, despite the channel quality not being at its peak. In such situations, exploiting channel-quality variations also in the frequency domain will help to improve the overall performance of the system. For LTE, scheduling decisions can be taken as often as once every 1 ms, and the granularity in the frequency domain is 180 kHz. This allows for relatively rapid channel variations in both the time and frequency domains to be tracked and utilized by the scheduler.

To support downlink scheduling, a device may provide the network with *channel-state* reports indicating the instantaneous downlink channel quality in both the time and frequency domains. The channel state is typically obtained by measuring on *reference signals* transmitted in the downlink. Based on the channel-state reports, also referred to as *channel-state information* (CSI), the downlink scheduler can assign resources for downlink transmission to different devices, taking the channel quality into account in the scheduling decision. In principle, a scheduled device can be assigned an arbitrary combination of 180 kHz wide *resource blocks* in each 1 ms scheduling interval.

As mentioned earlier in this chapter, the LTE uplink is based on orthogonal separation of different uplink transmissions, and it is the task of the uplink scheduler to assign resources in both the time and frequency domains to different devices. Scheduling decisions, taken once per 1 ms, control what set of devices are allowed to transmit within a cell during a given time interval and, for each device, on what frequency resources the transmission is to take place and what transmission parameters, including the data rate, to use. Similar scheduling strategies as in the downlink can be used, although there are some differences between the two. Fundamentally, the uplink power resource is *distributed* among the users, while in the downlink the power resource is *centralized* within the base station. Furthermore, the maximum uplink transmission power of a single terminal is typically significantly lower than the output power of a base station. This has a significant impact on the scheduling strategy. Unlike the downlink, where pure time division often can be used, uplink scheduling typically has to rely on sharing in the frequency domain in addition to the time domain, as a single terminal may not have sufficient power for efficiently utilizing the link capacity.

Channel conditions can also be taken into account in the uplink scheduling process, similar to the downlink scheduling. One possibility to acquire uplink CSI is through so-called *sounding*, where the terminal transmits a known reference signal from which the base station can assess the channel quality in the different parts of the spectrum. However, as is discussed in more detail in subsequent chapters, obtaining information about the uplink channel conditions may not be feasible or desirable in all situations. Therefore, different means to obtain *uplink diversity* are important as a complement in situations where uplink channel-dependent scheduling is not suitable.

3.1.3 INTER-CELL INTERFERENCE COORDINATION

LTE is designed to operate with a frequency reuse of one implying that the same carrier frequency can be used at neighboring transmission points. In particular, the basic control channels of LTE are designed to operate properly with the relatively low signal-to-interference ratio that may be experienced in a reuse-one deployment.

Fundamentally, having access to all available frequency resources at each transmission point is always beneficial. However, system efficiency and end-user quality are further improved if transmissions from neighboring transmission points can be coordinated in such a way that the most severe interference situations can be avoided.

Already the first release of LTE included explicit support for such coordination, in the release-8 context referred to as *inter-cell interference coordination* (ICIC), see Chapter 13. More specifically, the release-8 specifications defined a set of messages that can be exchanged between eNodeBs using the so-called *X2 interface*, see Chapter 4. These messages provide information about the interference situation experienced by the eNodeB issuing the message and can be used by a neighboring eNodeB receiving the message as input to its scheduling process, thereby providing a means for at least partly coordinating the transmissions and controlling the interference between cells of different eNodeBs. Especially severe interference situations may occur in so-called *heterogeneous network deployments* consisting of overlapping layers of base stations with large differences in the downlink transmission power. This is briefly discussed in Section 3.5, with a more in-depth discussion in Chapter 14.

3.1.4 MULTI-ANTENNA TRANSMISSION

Already from its first release, LTE has included support for different multi-antenna techniques as an integral part of the radio-interface specifications. In many respects, the use of multiple antennas is the key technology to reach many of the aggressive LTE performance targets. Multiple antennas can be used in different ways for different purposes:

- Multiple receive antennas can be used for receive diversity. For uplink transmissions, they have been used in many cellular systems for several years. However, as dual receive antennas are the baseline for all LTE devices,[2] the downlink performance is also improved. The simplest way of using multiple receive antennas is classical receive diversity to collect additional energy and suppress fading, but additional gains can be achieved in interference-limited scenarios if the antennas are used not only to provide diversity, but also to suppress interference.
- Multiple transmit antennas at the base station can be used for transmit diversity and different types of beam-forming. The main goal of beam-forming is to improve the received signal-to-interference-and-noise ratio (SINR) and, eventually, improve system capacity and coverage.
- *Spatial multiplexing*, sometimes referred to as multiple input, multiple output (MIMO) or more specifically single-user MIMO (SU-MIMO) using multiple antennas at both the transmitter and receiver, is supported by LTE. Spatial multiplexing results in an increased data rate, channel conditions permitting, in bandwidth-limited scenarios by creating several parallel "channels." Alternatively, by combining the spatial properties with the appropriate interference-suppressing receiver processing, multiple devices can transmit on the same time–frequency resource in order to improve the overall cell capacity. In 3GPP this is referred to as *multiuser MIMO*.

In general, the different multi-antenna techniques are beneficial in different scenarios. As an example, at relatively low SINR, such as at high load or at the cell edge, spatial multiplexing provides relatively limited benefits. Instead, in such scenarios multiple antennas at the transmitter side should be used to raise the SINR by means of beam-forming. On the other hand, in scenarios where there already is a relatively high SINR, for example, in small cells, raising the signal quality further provides relatively minor gains as the achievable data rates are then mainly bandwidth limited rather than SINR limited. In such scenarios, spatial multiplexing should instead be used to fully exploit the good channel conditions. The multi-antenna scheme used is under control of the base station, which therefore can select a suitable scheme for each transmission.

[2]For low-end MTC devices single-antenna operation is the baseline.

Release 9 enhanced the support for combining spatial multiplexing with beam-forming. Although the combination of beam-forming and spatial multiplexing was already possible in release 8, it was restricted to so-called *codebook-based precoding* (see Chapter 6). In release 9, the support for spatial multiplexing combined with so-called *non-codebook-based precoding* was introduced, allowing for improved flexibility in deploying various multi-antenna transmission schemes.

Up to four layers downlink spatial multiplexing was already supported from the first release of LTE. Later releases further extended the LTE multi-antenna capabilities as described in Section 3.4.

3.1.5 SPECTRUM FLEXIBILITY

A high degree of spectrum flexibility is one of the main characteristics of the LTE radio-access technology. The aim of this spectrum flexibility is to allow for the deployment of LTE radio access in difference frequency bands with various characteristics, including different duplex arrangements and different sizes of the available spectrum. Chapter 22 outlines further details of how spectrum flexibility is achieved in LTE.

3.1.5.1 Flexibility in duplex arrangements

One important part of the LTE requirements in terms of spectrum flexibility is the possibility to deploy LTE-based radio access in both paired *and* unpaired spectra. Therefore, LTE supports both frequency- and time-division-based duplex arrangements. *Frequency-division duplex* (FDD), as illustrated on the left in Figure 3.3, implies that downlink and uplink transmission take place in different, sufficiently separated, frequency bands. *Time-division duplex* (TDD), as illustrated on the right in Figure 3.3, implies that downlink and uplink

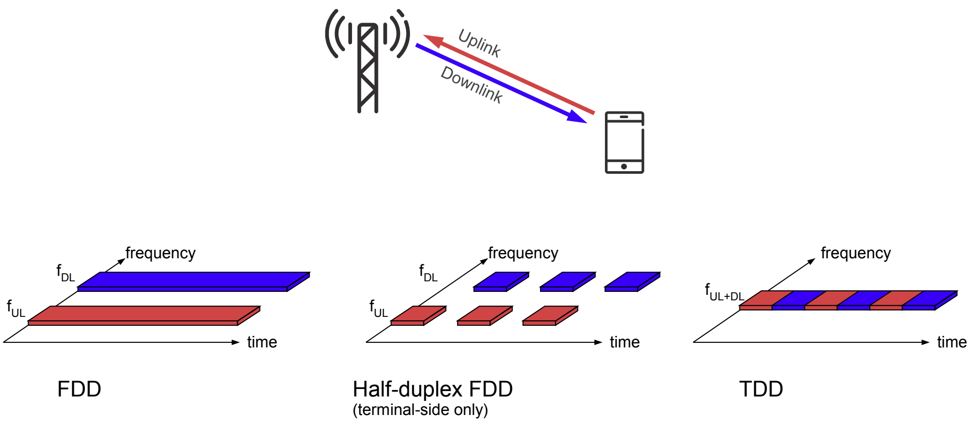

FIGURE 3.3

Frequency- and time-division duplex.

transmission take place in different, nonoverlapping time slots. Thus, TDD can operate in unpaired spectrum, whereas FDD requires paired spectrum. The required flexibility and resulting requirements to support LTE operation in different paired and unpaired frequency arrangements are further discussed in Chapter 22.

Operation in both paired and unpaired spectrum has been supported by 3GPP radio-access technologies even before the introduction of LTE by means of FDD-based WCDMA/HSPA in combination with TDD-based TD-SCDMA radio. However, this was then achieved by means of, at least in the details, relatively different radio-access technologies leading to additional effort and complexity when developing and implementing dual-mode devices capable of both FDD and TDD operation. LTE, on the other hand, supports both FDD and TDD *within a single radio-access technology*, leading to a minimum of deviation between FDD and TDD for LTE-based radio access. As a consequence of this, the overview of the LTE radio access provided in the following chapters is, to a large extent, valid for both FDD and TDD. In the case of differences between FDD and TDD, these differences are explicitly indicated. Furthermore, the TDD mode, also known as TD-LTE, is designed with coexistence between LTE (TDD) and TD-SCDMA in mind to simplify a gradual migration from TD-SCDMA to LTE.

LTE also supports *half-duplex* FDD at the device (illustrated in the middle of Figure 3.3). In half-duplex FDD, transmission and reception *at a specific device* are separated in both frequency and time. The base station still uses full-duplex FDD as it simultaneously may schedule *different* devices in uplink and downlink; this is similar to, for example, GSM operation. The main benefit with half-duplex FDD is the reduced device complexity as no duplex filter is needed in the device. This is especially beneficial in the case of multiband devices which otherwise would need multiple sets of duplex filters.

3.1.5.2 Bandwidth flexibility

An important characteristic of LTE is the support for a range of different transmission bandwidths on both downlink and uplink. The main reason for this is that the amount of spectrum available for LTE deployment may vary significantly between different frequency bands and also depending on the exact situation of the operator. Furthermore, the possibility of operating in different spectrum allocations gives the possibility for gradual migration of spectrum from other radio-access technologies to LTE.

LTE supports operation in a wide range of spectrum allocations, achieved by a flexible transmission bandwidth being part of the LTE specifications. To efficiently support very high data rates when spectrum is available, a wide transmission bandwidth is necessary. However, a sufficiently large amount of spectrum may not always be available, either due to the band of operation or due to a gradual migration from another radio-access technology, in which case LTE can be operated with a narrower transmission bandwidth. In such cases, the maximum achievable data rates will be reduced accordingly. As discussed in the following, the spectrum flexibility is further improved in later releases of LTE.

The LTE physical-layer specifications [24–27] are bandwidth agnostic and do not make any particular assumption on the supported transmission bandwidths beyond a minimum value. As is seen in the following, the basic radio-access specification, including the physical-layer and protocol specifications, allows for any transmission bandwidth ranging from roughly 1 MHz up to around 20 MHz. At the same time, at an initial stage, RF requirements are only specified for a limited subset of transmission bandwidths, corresponding to what is predicted to be relevant spectrum-allocation sizes and relevant migration scenarios. Thus, in practice the LTE radio-access technology supports a limited set of transmission bandwidths, but additional transmission bandwidths can easily be introduced by updating only the RF specifications.

3.1.6 MULTICAST AND BROADCAST SUPPORT

In situations where a large number of users want to receive the same information, for example, a TV news clip, information about the local weather conditions, or stock-market information, separate transmission of the information to each user may not be the most efficient approach. Instead, transmitting the same information once to all interested users may be a better choice. This is known as *broadcast*, or *multimedia broadcast–multicast services* (MBMS) in 3GPP, implying transmission of the same information to multiple receivers. In many cases the same information is of interest over a large area in which case identical signals can be transmitted from multiple cell sites with identical coding and modulation and with timing and frequency synchronized across the sites. From a device perspective, the signal will appear exactly as a signal transmitted from a single cell site and subject to multipath propagation, see Figure 3.4. Due to the OFDM robustness to multipath propagation, such multicell transmission, in 3GPP also referred to as *multicast/broadcast single-frequency network* (MBSFN) transmission, will then not only improve the received signal strength, but also eliminate the inter-cell interference. Thus, with OFDM, multicell broadcast/multicast throughput may eventually be limited by noise only and can then, in the case of small cells, reach extremely high values.

It should be noted that the use of MBSFN transmission for multicell broadcast/multicast assumes the use of tight synchronization and time alignment of the signals transmitted from different cell sites.

MBSFN support was part of the LTE work from the beginning, but due to time limitations, the support was not completed until the second release of LTE, release 9. There are also

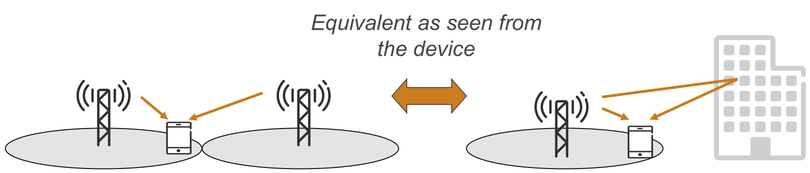

FIGURE 3.4

Equivalence between broadcast and multipath propagation from a device perspective.

enhancements for supporting multicast/broadcast services in a single cell in release 13, known as *single-cell point to multi-point* (SC-PTM).

3.1.7 POSITIONING

Positioning, as the name implies, refers to functionality in the radio-access network to determine the location of individual devices. Determining the position of a device can, in principle, be done by including a GPS receiver in the device. Although this is a quite common feature, not all devices include the necessary GPS receiver and there may also be cases when the GPS service is not available. LTE release 9 therefore introduced positioning support inherent in the radio-access network. By letting the device measure and report to the network the relative time of arrival of special reference signals transmitted regularly from different cell sites, the location of the device can be determined by the network.

3.2 LTE EVOLUTION

Releases 8 and 9 form the foundation of LTE, providing a highly capable mobile-broadband standard. However, to meet new requirements and expectations, the releases following the basic ones provides additional enhancements and features in different areas. Figure 3.5 illustrates some of the major areas in which LTE has been enhanced with details provided in the following. Table 3.1 captures the major enhancements per release.

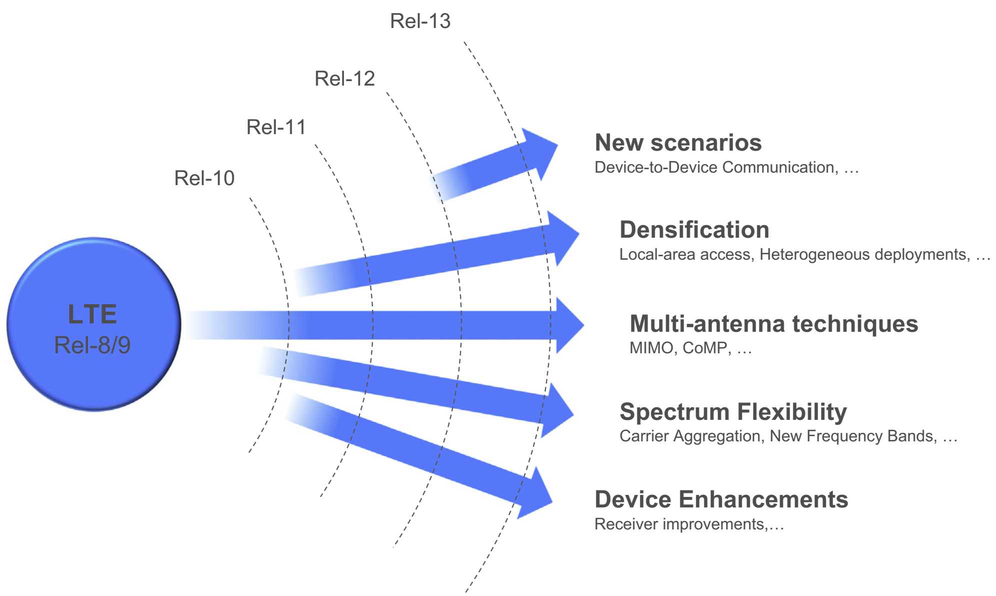

FIGURE 3.5

LTE evolution.

Table 3.1 Major LTE Features per Release

	Release 10	Release 11	Release 12	Release 13
New scenarios			• Device-to-device communication • Machine-type communication	• Enhancements for device-to-device communication • Enhancements for machine-type communication • Narrow-band IoT
Device enhancements		• Performance requirements for interference-rejection receivers	• Network-assisted interference cancellation • SIC, IRC for SU-MIMO	
Densification	• Heterogeneous deployments • Relaying	• Heterogeneous deployments	• Dual connectivity • Small-cell on/off • Dynamic TDD • Mobility enhancements in heterogeneous deployments	• Dual connectivity • License-assisted access
Multi-antenna techniques	• Downlink 8×8 MIMO • Uplink 4×4 MIMO	• CoMP with low-latency backhaul • Enhanced control-channel structures	• CoMP with nonideal backhaul	• FD-MIMO
Spectrum flexibility	• Carrier aggregation	• Carrier aggregation across different TDD configurations	• Carrier aggregation, FDD + TDD	• Carrier aggregation, up to 32 carriers • License-assisted access
Miscellaneous			• Smart congestion mitigation	• SC-PTM

Release 10 marks the start of the LTE evolution. One of the main targets of LTE release 10 was to ensure that the LTE radio-access technology would be fully compliant with the IMT-Advanced requirements, thus the name *LTE-Advanced* is often used for LTE release 10 and later. However, in addition to the ITU requirements, 3GPP also defined its own targets and requirements for LTE-Advanced [29]. These targets/requirements extended the ITU requirements both in terms of being more aggressive as well as including additional requirements. One important requirement was *backward compatibility*. Essentially this means that an earlier-release LTE device should be able to access a carrier supporting LTE release-10 functionality, although obviously not being able to utilize all the release-10 features of that carrier.

LTE release 10 was completed in late 2010 and implied enhanced LTE spectrum flexibility through carrier aggregation, further extended multi-antenna transmission, introduced support for relaying, and provided improvements in the area of interference coordination in heterogeneous network deployments.

Release 11 further extended the performance and capabilities of LTE. One of the most notable features of LTE release 11, finalized in late 2012, was radio-interface functionality for *coordinated multi-point* (CoMP) transmission and reception. Other examples of improvements in release-11 were carrier-aggregation enhancements, a new control-channel structure, and performance requirements for more advanced device receivers.

Release 12 was completed in 2014 and focused on small cells with features such as dual connectivity, small-cell on/off, and *enhanced Interference Mitigation and Traffic Adaptation* (eIMTA), as well as on new scenarios with introduction of direct device-to-device communication and provisioning of complexity-reduced machine-type communication.

Release 13, finalized at the end of 2015, marks the start of *LTE-Advanced Pro*. It is sometimes in marketing dubbed 4.5G and seen as an intermediate technology between 4G defined by the first releases of LTE and the upcoming new 5G air interface (see Chapters 23 and 24). License-assisted access (LAA) to support unlicensed spectrum as a complement to licensed spectrum, improved support for machine-type communication, and various enhancements in CA, multi-antenna transmission, and device-to-device communication are some of the highlights from release 13.

3.3 SPECTRUM FLEXIBILITY

Already the first release of LTE provides a certain degree of spectrum flexibility in terms of multi-bandwidth support and a joint FDD/TDD design. In later releases this flexibility was considerably enhanced to support higher bandwidths and fragmented spectrum using CA and access to unlicensed spectrum as a complement using license-assisted access (LAA).

3.3.1 CARRIER AGGREGATION

As mentioned earlier, the first release of LTE already provided extensive support for deployment in spectrum allocations of various characteristics, with bandwidths ranging from roughly 1 MHz up to 20 MHz in both paired and unpaired bands. With LTE release 10 the transmission bandwidth can be further extended by means of so-called carrier aggregation, where multiple *component carriers* are aggregated and jointly used for transmission to/from a single device. Up to five component carriers, possibly each of different bandwidth, can be aggregated in release 10, allowing for transmission bandwidths up to 100 MHz. All component carriers need to have the same duplex scheme and, in case of TDD, uplink–downlink configuration. In later releases, this requirement was relaxed, as well as the number of component carriers possible to aggregate was increased to 32, resulting in a total bandwidth of 640 MHz. Backward compatibility was ensured as each component carrier uses the release-8 structure. Hence, to a release-8/9 device each component carrier will appear as an LTE release-8 carrier, while a carrier-aggregation-capable device can exploit the total aggregated bandwidth, enabling higher data rates. In the general case, a different number of component carriers can be aggregated for the downlink and uplink. This is an important property from a device complexity point of view where aggregation can be supported in the downlink where very high data rates are needed without increasing the uplink complexity.

Component carriers do not have to be contiguous in frequency, which enables exploitation of *fragmented spectrum*; operators with a fragmented spectrum can provide high-data-rate services based on the availability of a wide overall bandwidth even though they do not possess a single wideband spectrum allocation.

From a baseband perspective, there is no difference between the cases in Figure 3.6, and they are all supported by LTE release 10. However, the RF-implementation complexity is vastly different with the first case being the least complex. Thus, although carrier aggregation is supported by the basic specifications, not all devices will support it. Furthermore, release 10 has some restrictions on carrier aggregation in the RF specifications, compared to what has been specified for physical layer and signaling, while in later releases there is support for CA within and between a much larger number of bands.

Release 11 provided additional flexibility for aggregation of TDD carriers. Prior to release 11, the same downlink–uplink allocation was required for all the aggregated carriers. This can be unnecessarily restrictive in case of aggregation of different bands as the configuration in each band may be given by coexistence with other radio-access technologies in that particular band. An interesting aspect of aggregating different downlink–uplink allocations is that the device may need to receive and transmit simultaneously in order to fully utilize both

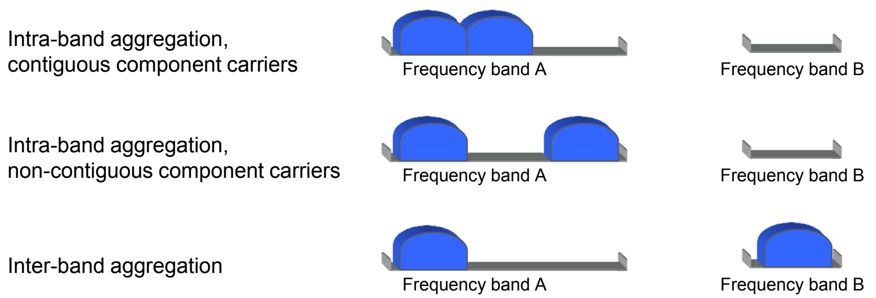

FIGURE 3.6

Carrier aggregation.

carriers. Thus, unlike previous releases, a TDD-capable device may, similarly to a FDD-capable device, need a duplex filter. Release 11 also saw the introduction of RF requirements for inter-band and noncontiguous intra-band aggregation, as well as support for an even larger set of inter-band aggregation scenarios.

Release 12 defined aggregations between FDD and TDD carriers, unlike earlier releases that only supported aggregation within one duplex type. FDD–TDD aggregation allows for efficient utilization of an operator's spectrum assets. It can also be used to improve the uplink coverage of TDD by relying on the possibility for continuous uplink transmission on the FDD carrier.

Release 13 increased the number of carriers possible to aggregate from 5 to 32, resulting in a maximum bandwidth of 640 MHz and a theoretical peak data rates around 25 Gbit/s in the downlink. The main motivation for increasing the number of subcarriers is to allow for very large bandwidths in unlicensed spectrum as is further discussed in conjunction with LAA.

The evolution of carrier aggregation is summarized in Figure 3.7 and further described in Chapter 12.

3.3.2 LICENSE-ASSISTED ACCESS

Originally, LTE was designed for licensed spectrum where an operator has an exclusive license for a certain frequency range. Licensed spectrum offers many benefits since the operator can plan the network and control the interference situation, but there is typically a cost associated with obtaining the spectrum license and the amount of licensed spectrum is limited. Therefore, using unlicensed spectrum as a *complement* to offer higher data rates and higher capacity in local areas is of interest. One possibility is to complement the LTE network with Wi-Fi, but higher performance can be achieved with a tighter coupling between licensed and unlicensed spectrum. LTE release 13 therefore introduced license-assisted access, where the carrier aggregation framework is used to aggregate downlink carriers in unlicensed frequency bands, primarily in the 5 GHz range, with carriers in licensed frequency bands as illustrated in Figure 3.8. Mobility, critical control signaling and services demanding high quality-of-service rely on carriers in the licensed spectrum while (parts of) less demanding traffic can be handled by the carriers using unlicensed spectrum. Operator-controlled

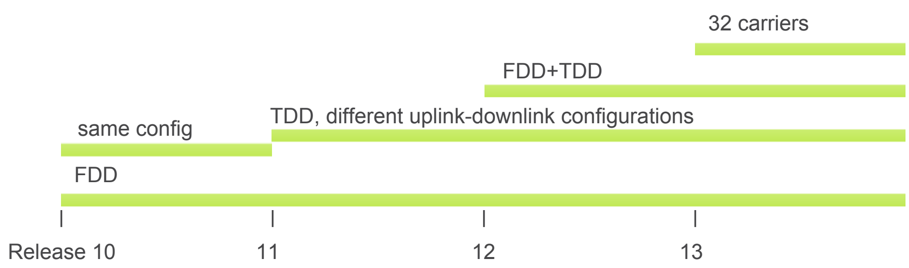

FIGURE 3.7

Evolution of carrier aggregation.

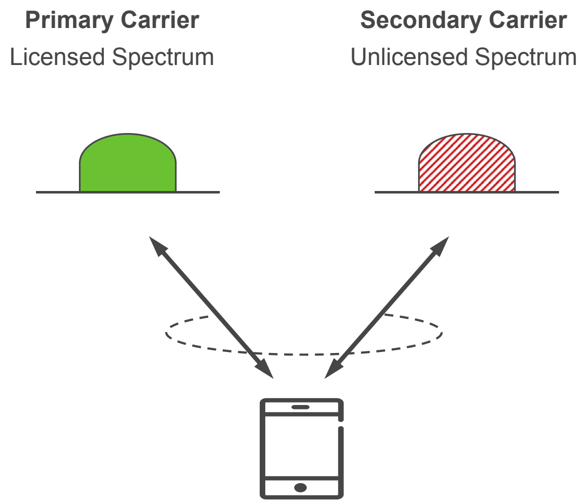

FIGURE 3.8

License-assisted access.

small-cell deployments is the target. Fair sharing of the spectrum resources with other systems, in particular Wi-Fi, is an important characteristic of LAA which therefore incudes a listen-before-talk mechanism.

Chapter 17 provides an in-depth discussion of license-assisted access.

3.4 MULTI-ANTENNA ENHANCEMENTS

Multi-antenna support has been enhanced over the different releases, increasing the number of transmission layers in the downlink to 8 and introducing uplink spatial multiplexing. Full-dimension MIMO (FD-MIMO) and two-dimensional beam-forming are other enhancements, as is the introduction of CoMP transmission.

3.4.1 EXTENDED MULTI-ANTENNA TRANSMISSION

In release 10, downlink spatial multiplexing was expanded to support up to eight transmission layers. This can be seen as an extension of the release-9 dual-layer beam-forming to support up to eight antenna ports and eight corresponding layers. Together with the support for carrier aggregation this enables downlink data rates up to 3 Gbit/s in 100 MHz of spectrum in release 10, increased to 25 Gbit/s in release 13 using 32 carriers, 8 layers spatial multiplexing and 256QAM.

Uplink spatial multiplexing of up to four layers was also introduced as part of LTE release 10. Together with the possibility for uplink carrier aggregation this allows for uplink data rates up to 1.5 Gbit/s in 100 MHz of spectrum. Uplink spatial multiplexing consists of a codebook-based scheme under control of the base station, which means that the structure can also be used for uplink transmitter-side beam-forming.

An important consequence of the multi-antenna extensions in LTE release 10 was the introduction of an enhanced downlink *reference-signal structure* that more extensively separated the function of channel estimation and the function of acquiring CSI. The aim of this was to better enable novel antenna arrangements and new features such as more elaborate multi-point coordination/transmission in a flexible way.

In release-13, improved support for a large number of antennas was introduced, in particular in terms of more extensive feedback of CSI. The larger degrees of freedom can be used for, for example, beam-forming in both elevation and azimuth and massive multiuser MIMO where several spatially separated devices are simultaneously served using the same time−frequency resource. These enhancements are sometimes termed full-dimension MIMO and form a step into massive MIMO with a very large number of steerable antenna elements.

The multi-antenna support is described as part of the general downlink processing in Chapter 6, uplink processing in Chapter 7, and the supporting CSI reporting mechanism in Chapter 10.

3.4.2 MULTI-POINT COORDINATION AND TRANSMISSION

As discussed earlier, the first release of LTE included specific support for coordination between transmission points, referred to as ICIC, as a means to at least partly control the interference between cells. However, the support for such coordination was significantly expanded as part of LTE release 11 including the possibility for much more dynamic coordination between transmission points.

In contrast to release-8 ICIC, which was limited to the definition of certain X2 messages to assist coordination between cells, the release 11 activities focused on radio-interface features and device functionality to assist different coordination means, including the support for channel-state feedback for multiple transmission points. Jointly these features and functionality go under the name CoMP transmission/reception. Refinement to the reference-signal structure was also an important part of the CoMP support, as was the enhanced control-channel structure introduced as part of release 11, see later.

Support for CoMP includes *multi-point coordination*, that is, when transmission to a device is carried out from one specific transmission point but where scheduling and link adaptation is coordinated between the transmission points, as well as *multi-point transmission* in which case transmission to a device can be carried out from multiple transmission points either in such a way that that transmission can switch dynamically between different transmission points (*Dynamic Point Selection*) or be carried out jointly from multiple transmission points (*Joint Transmission*), see Figure 3.9.

A similar distinction can be made for uplink where one can distinguish between (uplink) multi-point coordination and multi-point *reception*. In general, though uplink CoMP is

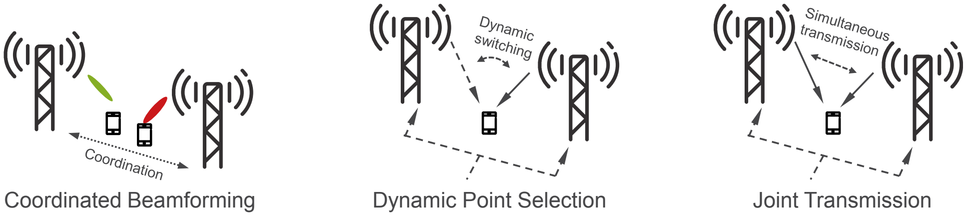

FIGURE 3.9

Different types of CoMP.

mainly a network implementation issue and has very little impact on the device and very little visibility in the radio-interface specifications.

The CoMP work in release 11 assumed "ideal" backhaul, in practice implying centralized baseband processing connected to the antenna sites using low-latency fiber connections. Extensions to relaxed backhaul scenarios with noncentralized baseband processing were introduced in release 12. These enhancements mainly consisted of defining new X2 messages for exchanging information about so-called CoMP hypotheses, essentially a potential resource allocation, and the associated gain/cost.

CoMP is described in more detail in Chapter 13.

3.4.3 ENHANCED CONTROL-CHANNEL STRUCTURE

In release 11, a new complementary control-channel structure was introduced in order to support ICIC and to exploit the additional flexibility of the new reference-signal structure not only for data transmission, which was the case in release 10, but also for control signaling. The new control-channel structure can thus be seen as a prerequisite for many CoMP schemes, although it is also beneficial for beam-forming and frequency-domain interference coordination. It is also used to support narrow-band operation for MTC enhancements in releases 12 and 13. A description of the enhanced control-channel structure is found in Chapter 6.

3.5 DENSIFICATION, SMALL CELLS, AND HETEROGENEOUS DEPLOYMENTS

Small cells and dense deployment has been in focus for several releases as means to provide very high capacity and data rates. Relaying, small-cell on/off, dynamic TDD, and heterogeneous deployments are some examples of enhancements over the releases. LAA, discussed in the area of spectrum flexibility, can also be seen as primarily an enhancement for small cells.

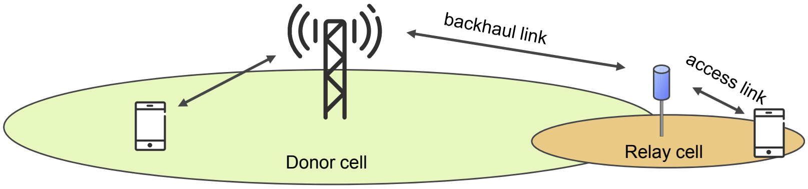

FIGURE 3.10

Example of relaying.

3.5.1 RELAYING

In the context of LTE, *relaying* implies that the device communicates with the network via a *relay node* that is *wirelessly connected* to a *donor cell* using the LTE radio-interface technology (see Figure 3.10). From a device point of view, the relay node will appear as an ordinary cell. This has the important advantage of simplifying the device implementation and making the relay node backward compatible—that is, also LTE release 8/9 devices can access the network via the relay node. In essence, the relay is a low-power base station wirelessly connected to the remaining part of the network, see Chapter 18 for more details.

3.5.2 HETEROGENEOUS DEPLOYMENTS

Heterogeneous deployments refer to deployments with a mixture of network nodes with different transmit power and overlapping geographic coverage (Figure 3.11). A typical example is a pico-node placed within the coverage area of a macrocell. Although such deployments were already supported in release 8, release 10 introduced new means to handle the interlayer interference that may occur between, for example, a pico-layer and the overlaid macro-layer as described in Chapter 14. The multi-point-coordination techniques introduced in release 11 further extends the set of tools for supporting heterogeneous deployments. Enhancements to improve mobility between the pico-layer and the macro-layer were introduced in release 12.

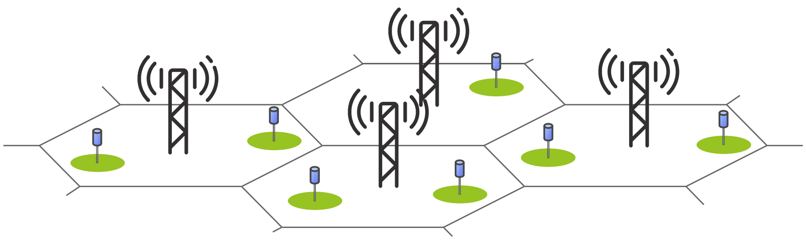

FIGURE 3.11

Example of heterogeneous deployment with low-power nodes inside macrocells.

3.5.3 SMALL-CELL ON-OFF

In LTE, cells are continuously transmitting cell-specific reference signals and broadcasting system information, regardless of the traffic activity in the cell. One reason for this is to enable idle-mode devices to detect the presence of a cell; if there were no transmissions from a cell there is nothing for the device to measure upon, and the cell would therefore not be detected. Furthermore, in a large macrocell deployment there is a relatively high likelihood of at least one device being active in a cell motivating continuous transmission of reference signals.

However, in a dense deployment with a large number of relatively small cells, the likelihood of not all cells serving device at the same time can be relatively high in some scenarios. The downlink interference scenario experienced by a device may also be more severe with devices experiencing very low signal-to-interference ratios due to interference from neighboring, potentially empty, cells, especially if there is a large amount of line-of-sight propagation. To address this, release 12 introduced mechanisms for turning on/off individual cells as a function of the traffic situation to reduce the average inter-cell interference and reduce power consumption. Chapter 15 describes these mechanisms in more detail.

3.5.4 DUAL CONNECTIVITY

Dual connectivity implies a device is simultaneously connected to two eNodeBs as opposed to the baseline case with a single eNodeB connected to the device. User-plane aggregation, where the device is receiving data transmission from multiple sites, separation of control and user planes, and uplink—downlink separation where downlink transmissions originates from a different node than the uplink reception node are some examples of the benefits with dual connectivity, see Chapter 16. To some extent it can be seen as carrier aggregation extended to the case of nonideal backhaul. The dual connectivity framework has also turned out to be very promising for integrating other radio-access schemes such as WLAN (wireless local-area network, for example Wi-Fi) into 3GPP networks. It will also play an important role in the 5G era for providing tight interworking between LTE and the new 5G radio-access technology as discussed in Chapter 23.

3.5.5 DYNAMIC TDD

In TDD, the same carrier frequency is shared in the time domain between uplink and downlink. The fundamental approach to this in LTE, as well as in many other TDD systems, is to statically split the resources in to uplink and downlink. Having a static split is a reasonable assumption in larger macrocells as there are multiple users and the aggregated per-cell load in uplink and downlink is relatively stable. However, with an increased interest in local-area deployments, TDD is expected to become more important compared to the situation for wide-area deployments to date. One reason is unpaired spectrum allocations being more common in higher-frequency bands not suitable for wide-area coverage.

Another reason is that many problematic interference scenarios in wide-area TDD networks are not present with below-rooftop deployments of small nodes. An existing wide-area FDD network could be complemented by a local-area layer using TDD, typically with low-output power per node.

To better handle the high traffic dynamics in a local-area scenario, where the number of devices transmitting to/receiving from a local-area access node can be very small, dynamic TDD is beneficial. In dynamic TDD, the network can dynamically use resources for either uplink or downlink transmissions to match the instantaneous traffic situation, which leads to an improvement of the end-user performance compared to the conventional static split of resources between uplink and downlink. To exploit these benefits, LTE release 12 includes support for dynamic TDD, or eIMTA as it the official name for this feature in 3GPP. More details on dynamic TDD can be found in Chapter 15.

3.5.6 WLAN INTERWORKING

The 3GPP architecture allows for integrating non-3GPP access, for example WLAN and also cdma2000 [74], into 3GPP networks. Essentially, these solutions connect the non-3GPP access to the EPC and are thus not visible in the LTE radio-access network. One drawback of this way of WLAN interworking is the lack of network control; the device may select Wi-Fi even if staying on LTE would provide a better user experience. One example of such a situation is when the Wi-Fi network is heavily loaded while the LTE network enjoys a light load. Release 12 therefore introduced means for the network to assist the device in the selection procedure. Basically, the network configures a signal-strength threshold controlling when the device should select LTE or Wi-Fi.

Release 13 provided further enhancements in the area of WLAN interworking with more explicit control from the LTE RAN on when a device should use Wi-Fi and when to use LTE. Furthermore, release 13 also includes LTE-WLAN aggregation where LTE and WLAN are aggregated at the PDCP level using a framework very similar to dual connectivity. Only downlink aggregation is currently supported.

3.6 DEVICE ENHANCEMENTS

Fundamentally, a device vendor is free to design the device receiver in any way as long as it supports the minimum requirements defined in the specifications. There is an incentive for the vendors to provide significantly better receivers as this could be directly translated into improved end-user data rates. However, the network may not be able to exploit such receiver improvements to their full extent as it might not know which devices have significantly better performance. Network deployments therefore need to be based on the minimum requirements. Defining performance requirements for more advanced receiver types to some extent alleviates this as the minimum performance of a device equipped with an advanced receiver is known. Both releases 11 and 12 saw a lot of focus on receiver improvements with cancellation of some overhead signals in release 11 and more generic schemes in release 12, including network-assisted interference cancellation and suppression (NAICS) where the network can provide the devices with information-assisting inter-cell interference cancellation.

3.7 NEW SCENARIOS

LTE was originally designed as a mobile broadband system, aiming at providing high data rates and high capacity over wide areas. The evolution of LTE has added features improving capacity and data rates, but also enhancements making LTE highly relevant also for new use cases, for example, massive machine-type communication. Operation in areas without network coverage, for example, in a disaster area, is another example, resulting in support for device-to-device communication being included in the LTE specifications in release 12.

3.7.1 DEVICE-TO-DEVICE COMMUNICATION

Cellular systems such as LTE are designed assuming that devices connect to a base station to communicate. In most cases this is an efficient approach as the server with the content of interest typically not being in the vicinity of the device. However, if the device is interested in communicating with a neighboring device, or just detect whether there is a neighboring device that is of interest, the network-centric communication may not be the best approach. Similarly, for public safety such as a first responder officer searching for people in need in a disaster situation, there is typically a requirement that communication should be possible also in absence of network coverage.

To address these situations, release 12 introduced network-assisted device-to-device communication using parts of the uplink spectrum. Two scenarios were considered when developing the device-to-device enhancements, in coverage as well as out-of-coverage communication for public safety, and in coverage discovery of neighboring devices for commercial use cases. More details on device-to-device communication in LTE can be found in Chapter 21.

In release 13, device-to-device communication was further enhanced with relaying solutions for extended coverage.

3.7.2 MACHINE-TYPE COMMUNICATION

Machine-type communication is a very wide term, basically covering all types of communication between machines. Although spanning a wide range of different applications, many of which are yet unknown, MTC applications can be divided into two main categories, massive MTC and critical MTC.

Examples of massive MTC scenarios are different types of sensors, actuators, and similar devices. These devices typically have to be of very low cost and have very low energy consumption enabling very long battery life. At the same time, the amount of data generated by each device is normally very small and very low latency is not a critical requirement. Critical MTC, on the other hand, corresponds to applications such as traffic safety/control or wireless connectivity for industrial processes, and in general where very high reliability and availability is required.

To better support massive MTC, several enhancements have been introduced starting with release 12 and the introduction of a new, low-end device category, category 0, supporting data rates up to 1 Mbit/s. A power-save mode for reduced device power consumption was also defined. Release 13 further improved the MTC support by defining category M1 with further extended coverage and support for 1.4 MHz device bandwidth, irrespective of the system bandwidth, to further reduce device cost. From a network perspective these devices are normal LTE devices, albeit with limited capabilities, and can be freely mixed with more capable LTE devices on a carrier.

Narrow-band Internet-of-Things, NB-IoT, is a parallel to the LTE track, to be completed in release 13. It targets even lower cost and data rates than category-M1, 250 kbit/s or less, in a bandwidth of 180 kHz, and even further enhanced coverage. Thanks to the use of OFDM with 15 kHz subcarrier spacing, it can be deployed inband on top of an LTE carrier, outband in a separate spectrum allocation, or in the guard bands of LTE, providing a high degree of flexibility for an operator. In the uplink, transmission on a single tone is supported to obtain very large coverage for the lowest data rates. NB-IoT uses the same family of higher-layer protocols (MAC, RLC, PDCP) as LTE, with extensions for faster connection setup applicable to both NB-IoT and category-M1, and can therefore easily be integrated into existing deployments.

Chapter 20 contains an in-depth description of massive MTC support in LTE.

3.8 DEVICE CAPABILITIES

To support different scenarios, which may call for different device capabilities in terms of data rates, as well as to allow for market differentiation in terms of low- and high-end devices with a corresponding difference in price, not all devices support all capabilities. Furthermore, devices from an earlier release of the standard will not support features introduced in later versions of LTE. For example, a release-8 device will not support carrier aggregation as this feature was introduced in release 10. Therefore, as part of the connection setup, the device indicates not only which release of LTE it supports, but also its capabilities within the release.

In principle, the different parameters could be specified separately, but to limit the number of combinations and avoid a parameter combination that does not make sense, a set of physical-layer capabilities are lumped together to form a UE category (UE, *User Equipment*, is the term used in 3GPP to denote a device). In total five different UE categories have been specified for LTE release 8/9, ranging from the low-end category 1 not supporting spatial multiplexing to the high-end category 5 supporting the full set of features in the release-8/9 physical-layer specifications. The categories are summarized in Table 3.2 (in simplified form with uplink and downlink categories merged in a single table; for the full set of details, see [30]). Note that, regardless of the category, a device is always capable of receiving single-stream transmissions from up to four antenna ports. This is necessary as the system information can be transmitted on up to four antenna ports.

In later releases, features such as carrier aggregation has been added calling for additional capability signaling compared to release 8/9 either in the form of additional UE categories or as separate capabilities. In order to be able to operate in networks following an earlier release a device has to be able to declare both release-8/9 category and categories for later releases.

Defining new categories for each foreseen combination of the maximum number of component carriers and maximum degree of spatial multiplexing could be done in

Table 3.2 UE Categories (Simplified Description)

		Downlink			Uplink	
Category	**Release**	**Peak Rate (Mbit/s)**	**Maximun Number of MIMO Layers**	**Maximum Modulation**	**Peak Rate (Mbit/s)**	**Maximum Modulation**
M1	13	0.2	1		0.14	
0	12	1	1	64QAM	1	16QAM
1	8	10	1	64QAM	5	16QAM
2	8	50	2	64QAM	25	16QAM
3	8	100	2	64QAM	50	16QAM
4	8	150	2	64QAM	50	16QAM
5	8	300	4	64QAM	75	64QAM
6	10	300	2 or 4	64QAM	50	16QAM
7	10	300	2 or 4	64QAM	100	16QAM
8	10	3000	8	64QAM	1500	64QAM
9	11	450	2 or 4	64QAM	50	16QAM
10	11	450	2 or 4	64QAM	100	16QAM
11	12	600	2 or 4	256QAM optional	50	16QAM
12	12	600	2 or 4	256QAM optional	100	16QAM
13	12	400	2 or 4	256QAM	150	64QAM
14	12	400	2 or 4	256QAM	100	16QAM
15	12	4000	8	256QAM		

principle, although the number of categories might become very large and which categories a device supports may be frequency-band dependent. Therefore, the maximum number of component carriers and degree of spatial multiplexing supported both in uplink and downlink, are signaled separately from the category number. Category-independent signaling is also used for several capabilities, especially for features added to LTE after the basic release 8/9. The duplexing schemes supported is one such example, and the support of UE-specific reference signals for FDD in release 8 is another. Whether the device supports other radio-access technologies, for example, GSM and WCDMA, is also declared separately.