CHAPTER

LTE—An Overview

4

The focus of this book is NR, the new 5G radio access. Nevertheless, a brief overview of LTE as background to the coming chapters is relevant. One reason is that both LTE and NR have been developed by 3GPP and hence have a common background and share several technology components. Many of the design choices in NR are also based on experience from LTE. Furthermore, LTE continues to evolve in parallel with NR and is an important component in 5G radio access. For a detailed description of LTE see [28].

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 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 subsequent LTE releases, introducing additional functionality and capabilities in different areas, as illustrated in Fig. 4.1. Releases 10 and 13 are particularly interesting. Release 10 is the first release of LTE-Advanced, and release 13, finalized in late 2015, is the first release of LTE-Advanced Pro. Currently, as of this writing, 3GPP is working on release 15 which, in addition to NR, also contains a further evolution of LTE.

4.1 LTE RELEASE 8—BASIC RADIO ACCESS

Release 8 is the first LTE release and forms the basis for all the following LTE releases. In parallel with the LTE radio access scheme, a new core network, the *Evolved Packet Core* (EPC) was developed [63].

One important requirement imposed on the LTE development was spectrum flexibility. A range of carrier bandwidths up to and including 20 MHz is supported for carrier frequencies from below 1 GHz up to around 3 GHz. One aspect of spectrum flexibility is the support of both paired *and* unpaired spectrum using *Frequency-Division Duplex* (FDD) and *Time-Division Duplex* (TDD), respectively, with a common design, albeit two different frame structures. The focus of the development work was primarily macronetworks with above-rooftop antennas and relatively large cells. For TDD, the uplink–downlink allocation is therefore in essence static with the same uplink–downlink allocation across all cells.

The basic transmission scheme in LTE is *orthogonal frequency-division multiplexing* (OFDM). This is an attractive choice due to its robustness to time

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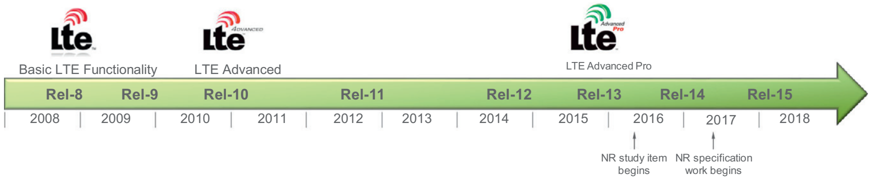

FIGURE 4.1

LTE and its evolution.

dispersion and ease of exploiting both the time and frequency domain. Furthermore, it also allows for reasonable receiver complexity also in combination with spatial multiplexing (MIMO) which is an inherent part of LTE. Since LTE was primarily designed with macronetworks in mind with carrier frequencies up to a few GHz, a single subcarrier spacing of 15 kHz and a cyclic prefix of approximately 4.7 μs[1] was found to be a good choice. In total 1200 subcarriers are used in a 20 MHz spectrum allocation.

For the uplink, where the available transmission power is significantly lower than for the downlink, the LTE design settled for a scheme with a low peak-to-average ratio to provide a high power-amplifier efficiency. DFT-precoded OFDM, with the same numerology as in the downlink, was chosen to achieve this. A drawback with DFT-precoded OFDM is the larger complexity on the receiver side, but given that LTE release 8 does not support spatial multiplexing in the uplink this was not seen as a major problem.

In the time domain, LTE organizes transmissions into 10-ms frames, each consisting of ten 1-ms subframes. The subframe duration of 1 ms, which corresponds to 14 OFDM symbols, is the smallest schedulable unit in LTE.

Cell-specific reference signals is a cornerstone in LTE. The base station continuously transmits one or more reference signals (one per layer), regardless of whether there are downlink data to transmit or not. This is a reasonable design for the scenarios which LTE was designed for—relatively large cells with many users per cell. The cell-specific reference signals are used for many functions in LTE: downlink channel estimation for coherent demodulation, channel-state reporting for scheduling purposes, correction of device-side frequency errors, initial access, and mobility measurements to mention just a few. The reference signal density depends on the number of transmission layers set up in a cell, but for the common case of 2×2 MIMO, every third subcarrier in four out of 14 OFDM symbols in a subframe are used for reference signals. Thus, in the time domain there are around 200 μs between reference signal occasions, which limits the possibilities to switch off the transmitter to reduce power consumption.

[1]There is also a possibility for 16.7 μs extended cyclic prefix but that option is rarely used in practice.

Data transmission in LTE is primarily scheduled on a dynamic basis in both uplink and downlink. To exploit the typically rapidly varying radio conditions, channel-dependent scheduling can be used. For each 1-ms subframe, the scheduler controls which devices are to transmit or receive and in what frequency resources. Different data rates can be selected by adjusting the code rate of the Turbo code as well as varying the modulation scheme from QPSK up to 64-QAM. To handle transmission errors, *fast hybrid ARQ with soft combining* is used in LTE. Upon downlink reception the device indicates the outcome of the decoding operation to the base station, which can retransmit erroneously received data blocks.

The scheduling decisions are provided to the device through the *Physical Downlink Control Channel* (PDCCH). If there are multiple devices scheduled in the same subframe, which is a common scenario, there are multiple PDCCHs, one per scheduled device. The first up to three OFDM symbols of the subframe are used for transmission of downlink control channels. Each control channel spans the full carrier bandwidth, thereby maximizing the frequency diversity. This also implies that all devices must support the full carrier bandwidth up to the maximum value of 20 MHz. Uplink control signaling from the devices, for example hybrid-ARQ acknowledgments and channel state information for downlink scheduling, is carried on the *Physical Uplink Control Channel* (PUCCH), which has a basic duration of 1 ms.

Multiantenna schemes, and in particular single-user MIMO, are an integral part of LTE. A number of transmission layers are mapped to up to four antennas by means of a precoder matrix of size $N_A \times N_L$, where the number of layers N_L, also known as the transmission rank, is less than or equal to the number of antennas N_A. The transmission rank, as well as the exact precoder matrix, can be selected by the network based on channel-status measurements carried out and reported by the terminal, also known as *closed-loop spatial multiplexing*. There is also a possibility to operate without closed-loop feedback for precoder selection. Up to four layers is possible in the downlink although commercial deployments typically use only two layers. In the uplink only single-layer transmission is possible.

In case of spatial multiplexing, by selecting rank-1 transmission, the precoder matrix, which then becomes an $N_A \times 1$ *precoder vector*, performs a (single-layer) *beam-forming* function. This type of beam-forming can more specifically be referred to as *codebook-based* beam-forming as the beam-forming can only be done according to a limited set of predefined beam-forming (precoder) vectors.

Using the basic features discussed above, LTE release 8 is in theory capable of providing peak data rates up to 150 Mbit/s in the downlink using two-layer transmission in 20 MHz and 75 Mbit/s in the uplink. Latency-wise LTE provides 8 ms roundtrip time in the hybrid-ARQ protocol and (theoretically) less than 5 ms one-way delay in the LTE RAN. In practical deployments, including transport and core network processing, an overall end-to-end latency of some 10 ms is not uncommon in well-deployed networks.

4.2 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 provide additional enhancements and features in different areas. Fig. 4.2 illustrates some of the major areas in which LTE has evolved over the 10 years since its introduction with details provided in the following.

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 [10]. These targets/requirements extended the ITU requirements both in terms of being more aggressive as well as including additional requirements. One important requirement was *backwards 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. The principle of backwards compatibility is important and has been kept for all LTE releases, but also imposes some restrictions on the enhancements possible; restrictions that are not present when defining a new standard such as NR.

LTE release 10 was completed in late 2010 and introduced enhanced LTE spectrum flexibility through carrier aggregation, further extended multiantenna transmission, support for relaying, and improvements around intercell interference coordination in heterogeneous network deployments.

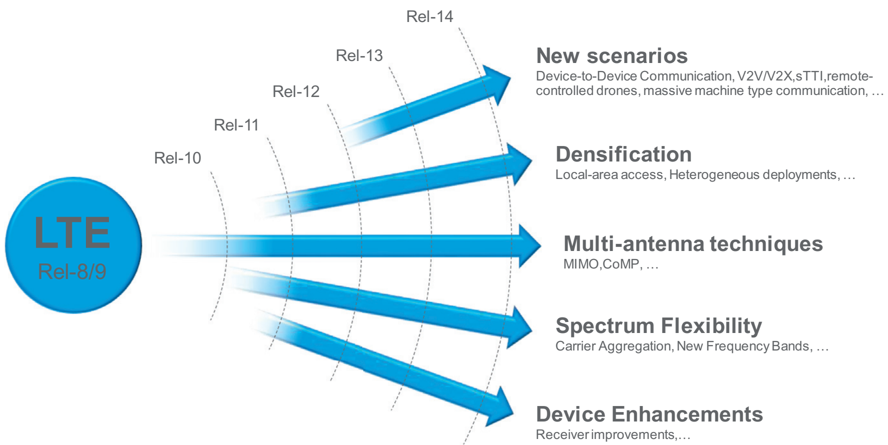

FIGURE 4.2

LTE evolution.

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 multipoint* (CoMP) transmission and reception. Other examples of improvements in release 11 were carrier-aggregation enhancements, a new control-channel structure (EPDCCH), 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 (semi-)dynamic TDD, 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 step between 4G defined by the first releases of LTE and the 5G NR air interface. License-assisted access to support unlicensed spectra as a complement to licensed spectra, improved support for machine-type communication, and various enhancements in carrier aggregation, multi-antenna transmission, and device-to-device communication are some of the highlights from release 13.

Release 14 was completed in the spring of 2017. Apart from enhancements to some of the features introduced in earlier releases, for example enhancements to operation in unlicensed spectra, it introduced support for vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication, as well as wide-area broadcast support with a reduced subcarrier spacing.

Release 15 will be completed in the middle of 2018. Significantly reduced latency through the so-called sTTI feature, as well as communication using aerials are two examples of enhancements in this release.

In general, expanding LTE to new use cases beyond traditional mobile broadband has been in focus for the later releases and the evolution will continue also in the future. This is also an important part of 5G overall and exemplifies that LTE remains important and a vital part of the overall 5G radio access.

4.3 SPECTRUM FLEXIBILITY

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

4.3.1 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 *carrier aggregation* (CA), 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 the case of TDD, uplink–downlink configuration. In later releases, this requirement was relaxed. The number of component carriers possible to aggregate was increased to 32, resulting in a total bandwidth of 640 MHz. Backwards 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 spectra*; 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 Fig. 4.3 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 related signaling, while in later releases there is support for carrier-aggregation within and between a much larger number of bands.

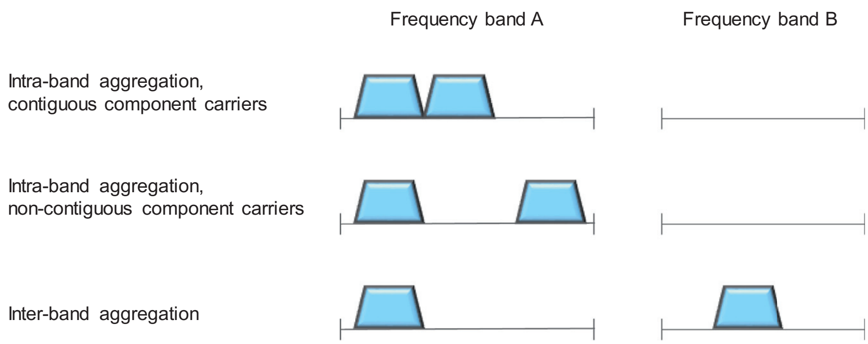

FIGURE 4.3

Carrier aggregation.

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 the 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 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 interband and noncontiguous intraband aggregation, as well as support for an even larger set of interband 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 rate 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 spectra as will be further discussed in conjunction with license-assisted access below.

Carrier aggregation is one of the most successful enhancements of LTE to date with new combinations of frequency band added in every release.

4.3.2 LICENSE-ASSISTED ACCESS

Originally, LTE was designed for licensed spectra where an operator has an exclusive license for a certain frequency range. A 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 spectra is limited. Therefore, using unlicensed spectra 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 spectra. 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 Fig. 4.4. Mobility, critical control signaling, and services demanding high quality-of-service rely on carriers in the licensed spectra while (parts of) less demanding traffic can be handled by the carriers using unlicensed spectra. Operator-controlled small-cell deployments are 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. In release 14, license-assisted access was enhanced to

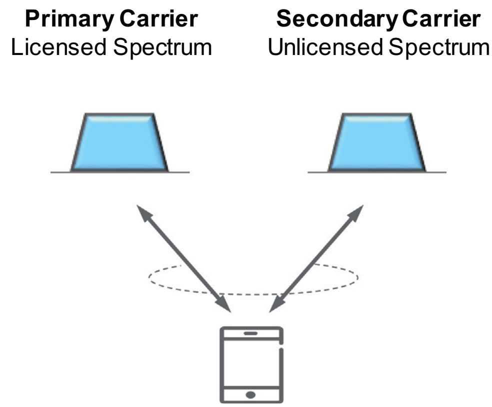

FIGURE 4.4

License-assisted access.

address also uplink transmissions. Although the LTE technology standardized in 3GPP supports license-assisted access only, where a licensed carrier is needed, there has been work outside 3GPP in the MulteFire alliance resulting in a stand-alone mode-of-operation based on the 3GPP standard.

4.4 MULTI-ANTENNA ENHANCEMENTS

Multi-antenna support has been enhanced over the different releases, increasing the number of transmission layers in the downlink to eight and introducing uplink spatial multiplexing of up to four layers. Full-dimension MIMO and two-dimensional beamforming are other enhancements, as is the introduction of coordinated multipoint transmission.

4.4.1 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 spectra in release 10, increased to 25 Gbit/s in release 13 using 32 carriers, eight 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 aggregations 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 the 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 multiantenna 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 channel-state information. The aim of this was to better enable novel antenna arrangements and new features such as more elaborate multipoint coordination/transmission in a flexible way.

In release 13, and continued in release 14, improved support for massive antenna arrays was introduced, primarily in terms of more extensive feedback of channel-state information. The larger degrees of freedom can be used for, for example, beamforming 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.

4.4.2 MULTIPOINT COORDINATION AND TRANSMISSION

The first release of LTE included specific support for coordination between transmission points, referred to as *Inter-Cell Interference Coordination* (ICIC), to 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 messages between base stations 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 *Coordinated Multi-Point* (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 below.

Support for CoMP includes *multipoint coordination*—that is, when transmission to a device is carried out from one specific transmission point but where scheduling and link adaptation are coordinated between the transmission points, as well as *multipoint 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 Fig. 4.5).

A similar distinction can be made for uplink where one can distinguish between (uplink) multipoint coordination and multipoint *reception*. In general,

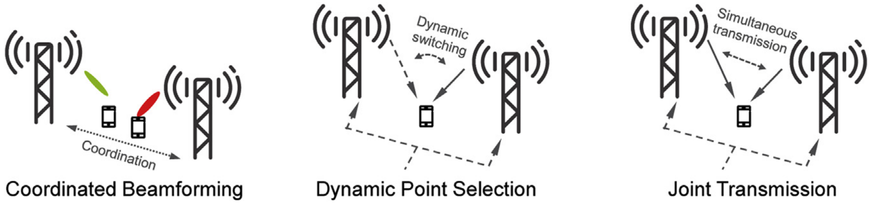

FIGURE 4.5

Different types of CoMP.

uplink CoMP is 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 non-centralized baseband processing were introduced in release 12. These enhancements mainly consisted of defining new X2 messages between base stations for exchanging information about so-called CoMP hypotheses, essentially a potential resource allocation, and the associated gain/cost.

4.4.3 ENHANCED CONTROL CHANNEL STRUCTURE

In release 11, a new complementary control channel structure was introduced to support intercell interference coordination 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 beamforming and frequency-domain interference coordination as well. It is also used to support narrow-band operation for MTC enhancements in releases 12 and 13.

4.5 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. License-assisted access, discussed in Section 4.3.2, is another feature primarily targeting small cells.

4.5.1 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

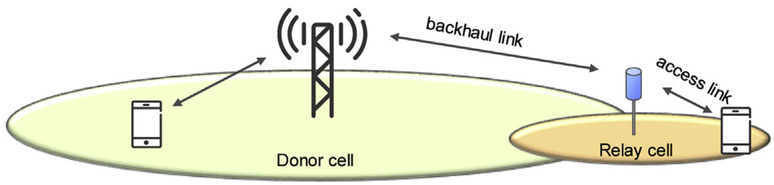

FIGURE 4.6

Example of relaying.

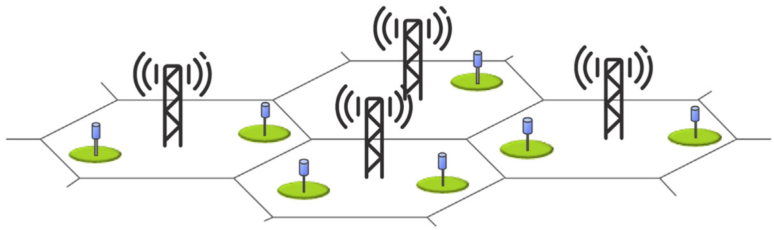

FIGURE 4.7

Example of heterogeneous deployment with low-power nodes inside macro cells.

LTE radio-interface technology (see Fig. 4.6). 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 backwards compatible—that is, LTE release-8/9 devices can also 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.

4.5.2 HETEROGENEOUS DEPLOYMENTS

Heterogeneous deployments refer to deployments with a mixture of network nodes with different transmit power and overlapping geographical coverage (Fig. 4.7). 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. The multipoint-coordination techniques introduced in release 11 further extend 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.

4.5.3 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 are 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 macro-cell 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 many relatively small cells, the likelihood of not all cells serving the 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 intercell interference and reduce power consumption.

4.5.4 DUAL CONNECTIVITY

Dual connectivity implies a device is simultaneously connected to two cells, see Fig. 4.8, as opposed to the baseline case with the device connected to a single device only. 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 originate from a different node than the uplink reception node are some examples of the benefits with dual connectivity. 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 into 3GPP networks. It is also essential for NR when operating in non-standalone mode with LTE providing mobility and initial access.

4.5.5 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.

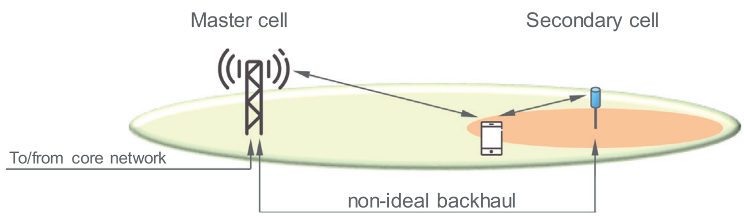

FIGURE 4.8

Example of dual connectivity.

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 *enhanced Interference Mitigation and Traffic Adaptation* (eIMTA) as is the official name for this feature in 3GPP.

4.5.6 WLAN INTERWORKING

The 3GPP architecture allows for integrating non-3GPP access, for example WLAN, but also cdma2000 [12]. 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 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.

4.6 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 (NAICS), where the network can provide the devices with information assisting intercell interference cancellation.

4.7 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. Operation in areas without network coverage, for example in a disaster area, is one example, resulting in support for device-to-device commination being included in the LTE. Massive machine-type communication, where a large number of low-cost devices, for example sensors, are connected to a cellular network is another example. V2V/V2X and remote-controlled drones are yet other examples of new scenarios.

4.7.1 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 is typically not in the vicinity of the device. However, if the device is interested in communicating with a neighboring device, or just detecting 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 also be possible in the absence of network coverage.

To address these situations, release 12 introduced network-assisted device-to-device communication using parts of the uplink spectrum (Fig. 4.9). 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. In release 13, device-to-device communication was further enhanced with relaying solutions

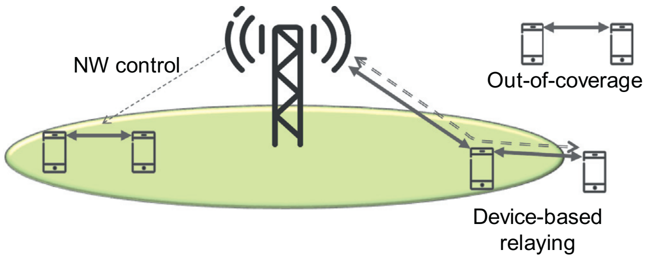

FIGURE 4.9

Device-to-device communciation.

for extended coverage. The device-to-device design also served as the basis for the V2V and V2X work in release 14.

4.7.2 MACHINE-TYPE COMMUNICATION

Machine-type communication (MTC) 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 ultrareliable low-latency communication (URLLC).

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. URLLC, on the other hand, corresponds to applications such as traffic safety/control or wireless connectivity for industrial processes, and in general scenarios where very high reliability and availability is required, combined with low latency.

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 LTE track 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, and 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.

Both eMTC and NB-IoT will play an important role in 5G networks for massive machine-type communication. Special means for deploying NR on top of an already-existing carrier used for massive machine-type communication has therefore been included (see Chapter 17).

Improved support for URLLC has been added in the later LTE releases. Examples hereof are the sTTI feature in release 15 (see below) and the general work on the reliability part of URLLC in release 15.

4.7.3 LATENCY REDUCTION—STTI

In release 15, work on reducing the overall latency has been carried out, resulting in the so-called *short TTI* (sTTI) feature. The target with this feature is to provide very low latency for use cases where this is important, for example factory automation. It uses similar techniques as used in NR, such as a transmission duration of a few OFDM symbols and reduced device processing delay, but incorporated in LTE in a backwards-compatible manner. This allows for low-latency services to be included in existing networks, but also implies certain limitations compared to a clean-slate design such as NR.

4.7.4 V2V AND V2X

Intelligent transportation systems (ITSs) refer to services to improve traffic safety and increase efficiency. Examples are vehicle-to-vehicle communication for safety, for example to transmit messages to vehicles behind when the car in front breaks. Another example is platooning where several trucks drive very close to each other and follow the first truck in the platoon, thereby saving fuel and reducing CO_2 emissions. Communication between vehicles and infrastructure is also useful, for example to obtain information about the traffic situation, weather updates, and alternative routes in case of congestion (Fig. 4.10).

In release 14, 3GPP specified enhancements in this area, based on the device-to-device technologies introduced in release 12 and quality-of-service enhancements in the network. Using the same technology for communication both between vehicles and between vehicles and infrastructure is attractive, both to improve the performance but also to reduce cost.

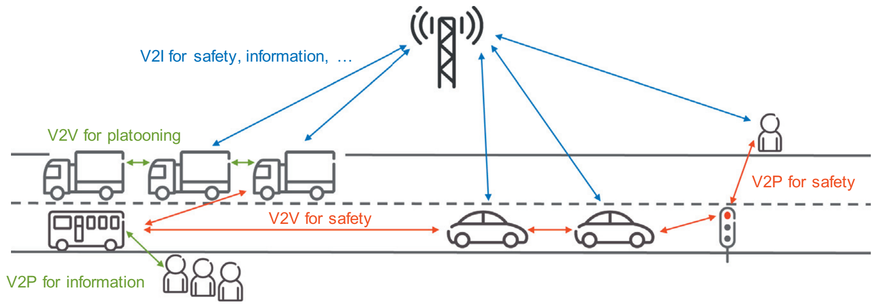

FIGURE 4.10

Illustration of V2V and V2X.

4.7.5 AERIALS

The work on aerials in release 15 covers communication via a drone acting as a relay to provide cellular coverage in an otherwise noncovered area, but also remote control of drones for various industrial and commercial applications. Since the propagation conditions between the ground and an airborne drone are different than in a terrestrial network, new channel models are developed as part of release 15. The interference situation for a drone is different than for a device on the groups due to the larger number of base stations visible to the drone, calling for interference-mitigation techniques such as beamforming, as well as enhancements to the power-control mechanism.