Evolution of LTE toward IMT-Advanced

Stefan Parkvall, Anders Furuskär, and Erik Dahlman, Ericsson Research

ABSTRACT

This article provides a high-level overview of LTE Release 10, sometimes referred to as LTE-Advanced. First, a brief overview of the first release of LTE and some of its technology components is given, followed by a discussion on the IMT-Advanced requirements. The technology enhancements introduced to LTE in Release 10, carrier aggregation, improved multi-antenna support, relaying, and improved support for heterogeneous deployments, are described. The article is concluded with simulation results, showing that LTE Release 10 fulfills and even surpasses the requirements for IMT-Advanced.

INTRODUCTION

Deployment of fourth-generation (4G) mobile-broadband systems based on the highly flexible Long Term Evolution (LTE) radio access technology [1, 2] defined by the Third Generation Partnership Project (3GPP) is currently ongoing on a broad scale, with the first systems already being in full commercial operation. These systems are based on the first release of LTE, 3GPP Release 8, which was finalized in 2008. Release 8 can provide downlink and uplink peak rates up to 300 and 75 Mb/s, respectively, a one-way radio-network delay of less than 5 ms, and a significant increase in spectrum efficiency. LTE provides extensive support for spectrum flexibility, supports both frequency-division duplex (FDD) and time-division duplex (TDD), and targets a smooth evolution from earlier 3GPP technologies such as time-division synchronous code-division multiple access (TD-SCDMA) and wideband CDMA (WCDMA)/high-speed pakcet access (HSPA) as well as 3GPP2 technologies such as cdma2000.

The LTE radio access technology is continuously evolving to meet future requirements. In Release 9, finalized at the end of 2009, support for broadcast/multicast services, positioning services, and enhanced emergency-call functionality, as well as enhancements for downlink dual-layer beam-forming, were added.

Recently, 3GPP has concluded the work on LTE Release 10, finalized at the end of 2010 and further extending the performance and capabilities of LTE beyond Release 8/9. An important aim of LTE Release 10 is to ensure that LTE fulfills all the requirements for International Mobile Telecommunications (IMT)-Advanced as defined by the International Telecommunication Union (ITU) [3, 4]. The relation to IMT-Advanced is also the reason for the label *LTE-Advanced* sometimes given to LTE Release 10 and beyond.

This article provides a brief overview of LTE Release 8/9 and a short introduction to the IMT-Advanced work. Following this background, the extensions introduced in Release 10 are described. The article is concluded with results from system-level evaluations showing that LTE Release 10 can fulfill and even surpass the IMT-Advanced requirements.

OVERVIEW OF LTE RELEASE 8

LTE is an orthogonal frequency-division multiplexing (OFDM)-based radio access technology, with conventional OFDM on the downlink and discrete Fourier transform spread OFDM (DFTS-OFDM) [1] on the uplink. DFTS-OFDM allows for more efficient power-amplifier operation, thus providing the opportunity for reduced terminal power consumption. At the same time, equalization of the received signal is straightforward with conventional OFDM. The use of OFDM on the downlink combined with DFTS-OFDM on the uplink thus minimizes terminal complexity on the receiver side (downlink) as well as on the transmitter side (uplink), leading to an overall reduction in terminal complexity and power consumption.

The transmitted signal is organized into subframes of 1 ms duration with 10 subframes forming a radio frame as illustrated in Fig. 1. Each downlink subframe consists of a control region of one to three OFDM symbols, used for control signaling from the base station to the terminals, and a data region comprising the remaining part and used for data transmission to the terminals. The data transmissions in each subframe are dynamically scheduled by the base station. As seen in Fig. 1, cell-specific reference signals are also transmitted in each downlink subframe. These reference signals are used for data demodulation at the terminal (or user equipment, UE), and for measurement purposes (e.g., for channel status reports sent from the terminals to the base station).

Spectrum flexibility is one of the key properties of the LTE radio access technology. A wide range of different bandwidths is defined and

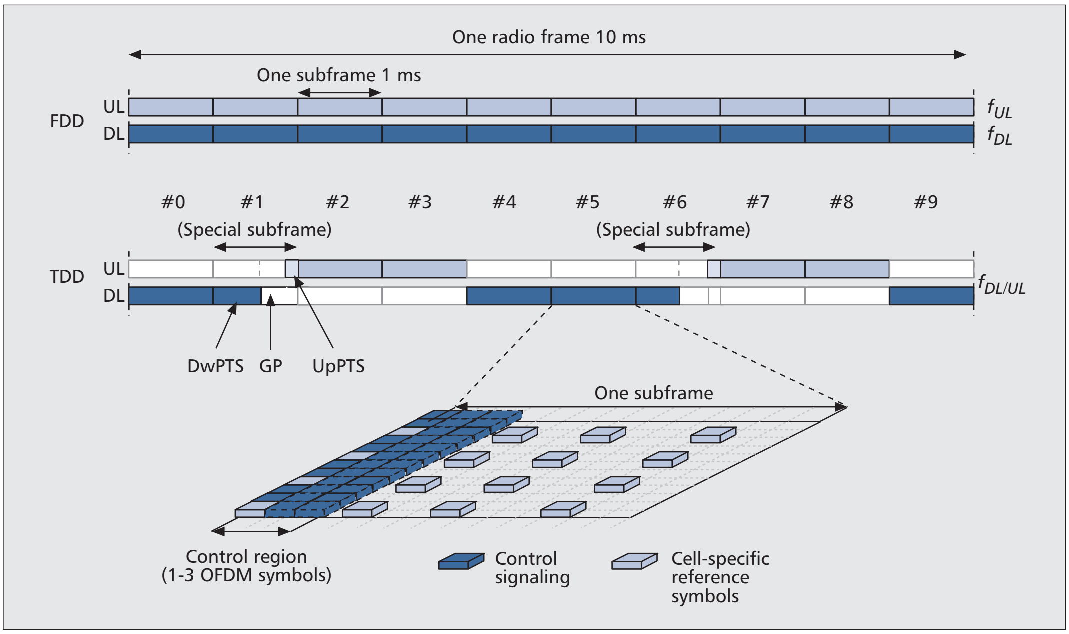

Figure 1. *LTE time-frequency structure.*

Support for multi-antenna transmission is an integral part of LTE from the first release. Downlink multi-antenna schemes supported by LTE include transmit diversity, spatial multiplexing (including both so-called single-user MIMO as well as multi-user MIMO), and beamforming.

both FDD and TDD modes of operation are supported, allowing for operation in both paired and unpaired spectrum. An important requirement in the LTE design has been to avoid unnecessary fragmentation and strive for commonality between the FDD and TDD modes of operation while still maintaining the possibility to fully exploit duplex-specific properties such as channel reciprocity in TDD. Aligning the two duplex schemes to the extent possible does not only increase the momentum in the definition and standardization of the technology but also further improves the economy of scale of the LTE radio access technology.

Support for multi-antenna transmission is an integral part of LTE from the first release. Downlink multi-antenna schemes supported by LTE include transmit diversity, spatial multiplexing (including both so-called single-user multiple-input multiple-output [MIMO] as well as multi-user MIMO), and beamforming.

ITU and IMT-Advanced

IMT-Advanced is the term used by ITU for radio access technologies beyond IMT-2000. An invitation to submit candidate technologies for IMT-Advanced was issued by ITU in 2008 [3]. Along with the invitation, ITU has also defined a set of requirements to be fulfilled by any IMT-Advanced candidate technology [4], some of which are shown in Table 1 together with the corresponding capabilities of LTE Release 10.

Anticipating the invitation from ITU, 3GPP already in March 2008 initiated a study item on LTE-Advanced, with the task of defining requirements and investigating potential technology components for the LTE evolution. This study item, completed in March 2010 and forming the basis for the Release 10 work, aimed *beyond* IMT-Advanced [5]. In 2010 3GPP submitted LTE Release 10 to ITU and, based on this submission, ITU approved LTE Release 10 as one of two IMT-Advanced technologies. As will be seen, Release 10 will not only fulfill the IMT-Advanced requirements but in many cases even surpass them.

LTE Release 10

LTE Release 10, sometimes known as LTE-Advanced, is not a new radio access technology but the evolution of LTE to further improve performance. Being an evolution of LTE, Release 10 includes all the features of Release 8/9 and adds several new features, the most important of which — carrier aggregation, enhanced multi-antenna support, improved support for heterogeneous deployments, and relaying — are discussed in the following sections. Evolving LTE rather than designing a new radio access technology is important from an operator perspective as it allows for smooth introduction of new technologies without jeopardizing existing investments. A Release 10 terminal can directly connect to a network of an earlier release, and a Release 8/9 terminal can connect to a network supporting the new enhancements. Hence, an operator can deploy a Release 8 network and later, when the need arises, upgrade to Release 10 functionality where needed. In fact, most of the Release 10 features can be introduced into the network as simple software upgrades.

Carrier Aggregation

Already the first release of LTE, Release 8, provides extensive support for deployment in spectrum allocations of various characteristics, with bandwidths ranging from around 1.4 up to 20 MHz in both paired and unpaired bands. In Release 10 the transmission bandwidth can be further extended by means of so-called *carrier aggregation* (CA) where multiple *component carriers* are aggregated and jointly used for transmission to/from a single mobile terminal, as illustrated in Fig. 2. Up to five component carri-

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	IMT-Advanced requirement	LTE Release 8	LTE Release 10
Transmission bandwidth	At least 40 MHz	Up to 20 MHz	Up to 100 MHz
Peak spectral efficiency – Downlink – Uplink	15 b/s/Hz 6.75 b/s/Hz	16 b/s/Hz 4 b/s/Hz	16.0 [30.0]* b/s/Hz 8.1 [16.1]** b/s/Hz
Latency – Control plane – User plane	Less than 100 ms Less than 10 ms	50 ms 4.9 ms	50 ms 4.9 ms

*Value is for a 4 × 4 antenna configuration. Value in brackets for 8 × 8.
** Values is for a 2 × 2 antenna configuration. Value in brackets for 4 × 4.

Table 1. *Requirements and LTE fulfillment.*

ers, possibly each of different bandwidth, can be aggregated, allowing for transmission bandwidths up to 100 MHz. Backward compatibility is catered for as each component carrier uses the Release 8 structure. Hence, to a Release 8/9 terminal each component carrier will appear as an LTE Release 8 carrier, while a carrier-aggregation-capable terminal can exploit the total aggregated bandwidth enabling higher data rates. In the general case, different numbers of component carriers can be aggregated for the downlink and uplink.

With respect to the frequency location of the different component carriers, three different cases can be identified: intra-band aggregation with contiguous carriers (e.g., aggregation of #2 and #3 in Fig. 2), inter-band aggregation (#1 and #4), and intra-band aggregation with non-contiguous carriers (#1 and #2). The possibility to aggregate non-adjacent component carriers enables exploitation of fragmented spectrum; operators with a fragmented spectrum can provide high-data-rate services based on the availability of 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, and they are all supported by LTE Release 10. However, the radio frequency (RF) implementation complexity is vastly different with the first case being the least complex. Thus, although spectrum aggregation is supported by the basic specifications, the actual implementation will be strongly constrained, including specification of only a limited number of aggregation scenarios and aggregation over dispersed spectrum only being supported by the most advanced terminals. Although exploitation of fragmented spectrum and expansion of the total bandwidth beyond 20 MHz are two important usages of carrier aggregation, there are also scenarios where carrier aggregation within 20 MHz of contiguous spectrum is useful. One example is heterogeneous deployments, discussed below.

Scheduling and hybrid automatic repeat request (ARQ) retransmissions are handled independently for each component carrier (Fig. 2). As a baseline, control signaling is transmitted on the same component carrier as the corresponding data. However, as a complement it is possible to use so-called *cross-carrier scheduling* where the scheduling decision is transmitted to the terminal on another component carrier than the corresponding data.

To reduce the terminal power consumption, a carrier-aggregation-capable terminal typically receives on one component carrier only, the *primary component carrier*. Reception of additional secondary component carriers can be rapidly turned on/off in the terminal by the base station through medium access control (MAC) signaling. Similarly, in the uplink all the feedback signaling is transmitted on the primary component carrier, and secondary component carriers are only enabled when necessary for data transmission.

Enhanced Multi-Antenna Support

LTE supports a rich set of multi-antenna transmission techniques already in the first release. This includes downlink transmit diversity based on space-frequency block coding (SFBC) for the case of two transmit antennas and SFBC in combination with frequency shift time diversity (FSTD) for four transmit antennas. In addition, downlink *codebook-based* precoding, including the possibility for multilayer transmission (spatial multiplexing) with up to four layers, is supported in LTE Release 8. This includes the possibility for rank-adaptation down to *single-layer* transmission, leading to codebook-based *beamforming*, as well as a basic form of *multi-user MIMO* where different layers in the same time-frequency resource can be assigned to different terminals.

The multi-antenna techniques above rely on the previously mentioned cell-specific reference signals for demodulation as well as to acquire channel-state feedback from the terminal to the base station. In addition, *UE-specific reference signals* are part of Release 8 to support single-layer beam-forming; support that is extended to dual-layer transmission in Release 9. UE-specific reference signals are pre-coded together with the data, implying that the pre-coder weights are not restricted to a certain codebook and do not need to be known to the receiver. An important application is beamforming with more than four antennas and, for TDD, reciprocity-based transmission strategies.

In Release 10, downlink spatial multiplexing is expanded to support up to eight transmission layers together with an enhanced reference signal structure. Relying on cell-specific reference signals for higher-order spatial multiplexing is less attractive since the reference signal overhead is not proportional to the instantaneous transmission rank but rather to the maximum supported transmission rank. Hence, Release 10 introduces extensive support of UE-specific reference signals for demodulation of up to eight layers. Furthermore, feedback of channel-state information (CSI) is based on a separate set of reference signals broadcasted in the cell, known as *CSI reference signals*. CSI reference signals are relatively sparse in frequency (every 12th subcarrier, corresponding to 180 kHz) but regularly transmitted from all antennas at the base station. The periodicity is configurable but is typically on order of once per 10 ms. UE-specific reference signals, on the other hand, are denser in frequency and only transmitted when data is transmitted on the corresponding layer. Separating the reference signal structure supporting demodulation from that supporting channel state estimation helps reduce the reference signal overhead, especially for high degrees of spatial multiplexing, and allows for implementation of various beamforming schemes.

Uplink spatial multiplexing of up to four layers is also part of Release 10. The basis is a codebook-based scheme where the scheduler in the base station determines the precoding matrix to be applied in the terminal. The selected precoding matrix is applied to uplink data transmissions as well as the uplink demodulation reference signals. To facilitate the selection of a suitable preceding matrix in the terminal, the sounding reference signals are enhanced to support up to four antennas.

Improved Support for Heterogeneous Deployments

With the rapidly growing usage of mobile broadband, the data rates experienced by the users in the network become increasingly important. The end-user data rate in a practical deployment is highly dependent on factors such as the terminal-to-base-station distance, whether the user is indoor or outdoor, and so on. As the possibilities to improve the link performance or increase the transmission power are limited, supporting very high end-user data rates requires a denser infrastructure. Not only does a densified network have the possibility to increase the data rates experienced, it can also increase the overall capacity as the number of sites increase. A straightforward densification of an existing macro network is one possibility, but in scenarios where the users are highly clustered, a potentially attractive approach is to complement a macro cell providing basic coverage with multiple low-output-power *pico* cells where needed as shown in Fig. 3. The result of such a strategy is a *heterogeneous deployment* with two or more cell layers. The idea of multiple cell layers is in itself not new; hierarchical cell structures have been discussed since the mid-'90s but then for (low-rate) voice users. It is important to point out that this is a deployment strategy, not a technology component, and as such is possible already

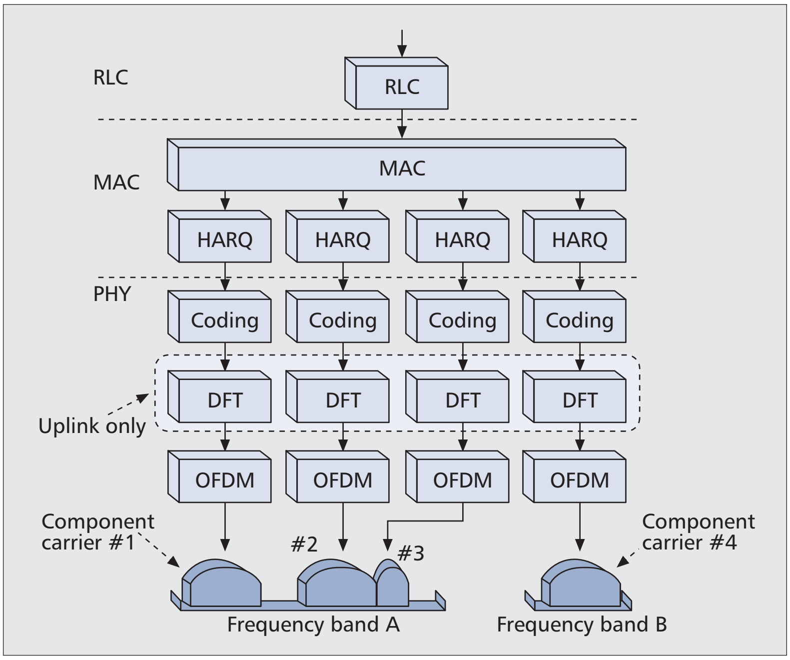

Figure 2. *Carrier aggregation in LTE Release 10.*

in LTE Release 8/9. However, Release 10 provides some additional features, improving the support for heterogeneous deployments.

In a heterogeneous deployment, cell association (i.e., to which cell a terminal should be connected) plays an important role. From an uplink data rate perspective, it is fundamentally beneficial to connect to the cell with the lowest path loss as this results in a higher data rate at a given transmit power, instead of the traditional approach of connecting to the cell with the strongest received downlink. The best cell for downlink association depends on the load; at low load connecting to the cell with the strongest received downlink offers the highest data rates, while at high loads connecting to the low-power node may be preferable as it provides for downlink resource reuse between the cells served by the low-power nodes. The backhaul capacity to the low-power node is also important to consider. Cell association strategies in a heterogeneous deployment are therefore nontrivial where the overall network performance must be taken into account. Nevertheless, any cell association strategy not solely based on maximizing the received downlink signal quality can lead to a new interference situation in the network as, in essence, the uplink coverage area can be larger than the downlink coverage area, implying that there is a region around the low-power node (lighter ring in Fig. 3) where downlink transmission from the low-power node to a terminal is subject to strong interference from the macrocell. The signal-to-interference ratio experienced by the terminal at the outermost coverage area of the low-power node is, due to the difference in output power between the high-power macro and the low-power node, significantly lower than in a traditional homogeneous macro network.

For the data part of a subframe, this is not a serious problem as the *intercell interference coordination* (ICIC) mechanism present in LTE

To provide for accurate CSI feedback, Release 10 provides the possibility to configure which subframes the terminal should base it channel-quality estimates upon as the interference experience by a terminal connected to a low-power node may vary drastically depending on the macro cell activity.

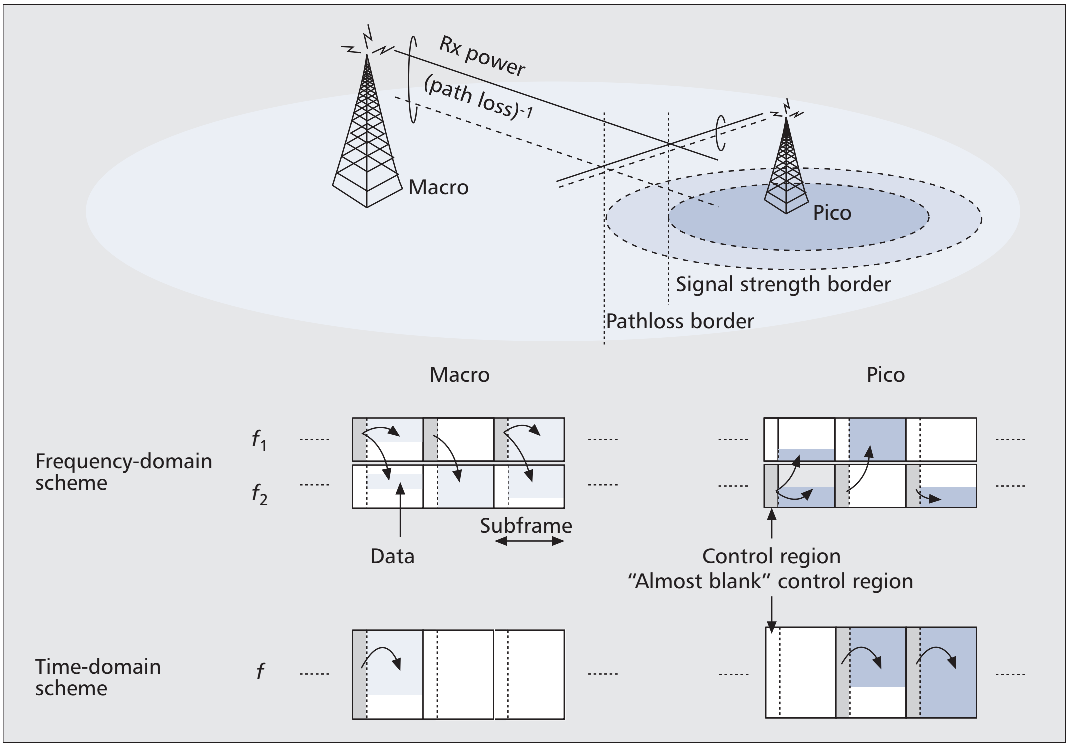

Figure 3. *Heterogeneous deployment with a macro cell overlaying multiple pico cells.*

already from Release 8 can be used. With ICIC, different cells can exchange information about which frequencies they intend to schedule transmissions on in the near future, thereby reducing or completely avoiding intercell interference. This can be used to more or less dynamically coordinate the resource usage between the cell layers and avoid overlapping resource usage.

The control signaling in each subframe is more problematic as it spans the full cell bandwidth and is not subject to ICIC. To address this, LTE Release 10 provides enhancements to separate the control signaling for the different cell layers in either the frequency or time domain.

Frequency domain schemes use carrier aggregation to separate control signaling for the different cell layers. At least one component carrier in each cell layer is protected from interference from other cell layers by not transmitting control signaling on the component carrier in question in the other cell layers. For example, referring to Fig. 3, the macro base station transmits control signaling on component carrier f_1 but not on component carrier f_2, while the situation is the opposite in the low-power nodes located within the macrocell. Since Release 10 introduces cross-carrier scheduling, resources on f_2 can be used for data transmission, scheduled by control signaling received on f_1, subject to the normal ICIC mechanism. In essence, this creates frequency reuse for the control signaling while still allowing terminals to dynamically utilize the full bandwidth (and thereby supporting the highest data rates) for the data part. For example, an operator with 20 MHz of spectrum may choose to configure two component carriers of 10 MHz each and use carrier aggregation as described above. Note that carrier-aggregation-capable terminals, in addition to benefits of connecting to the low-power node, also in the lighter ring in Fig. 3, will have the same peak data rates as in the case of a single 20 MHz carrier. Release 8/9 can also benefit from seeing a *larger* picocell but can obviously only access one component carrier.

Time domain schemes use a single component carrier f in all the cell layers and separate the control signaling in the different cell layers in the time domain, as seen in Fig. 3. At least some subframes in the low-power cell layer are protected from interference by the macro layer muting the control signaling in those subframes. However, for backward compatibility, cell-specific reference signals still needs to be transmitted from the macro cell, resulting in some interference to the terminals. To provide for accurate CSI feedback, Release 10 provides the possibility to configure on which subframes the terminal should base its channel-quality estimates as the interference experienced by a terminal connected to a low-power node may vary drastically depending on the macrocell activity. Note that in this approach, Release 8/9 terminals will connect to the macro and not to the low-power node in the lighter area in Fig. 3, but can access the full bandwidth of the carrier.

The discussion above assumes that the terminals are allowed to connect to the low-power node. This is known as *open access*, and typically the low-power nodes are operator-deployed in such a scenario. Another scenario, giving rise to a similar interference problem, is user-deployed home base stations. The term *closed subscriber groups* (CSGs) is commonly used to refer to cases when access to such a low-power base station is limited to a small set of terminals (e.g., a family living in a house where the home base station is located). CSG results in additional interference scenarios. For example, a terminal

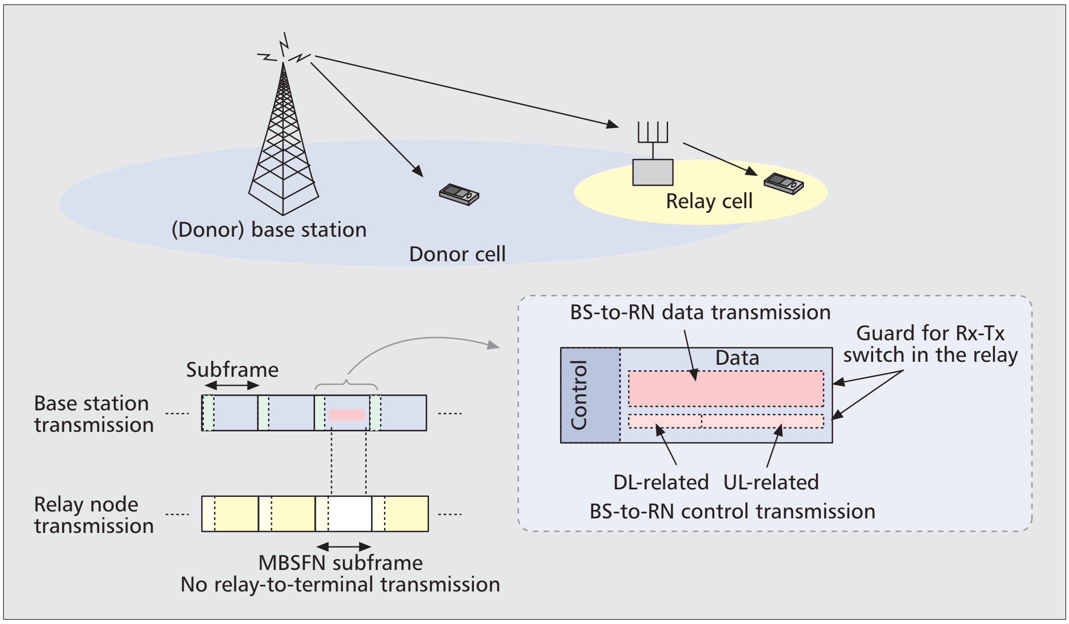

Figure 4. *Relaying.*

In essence, the relay is a low-power base station wirelessly connected to the remaining part of the network. One of the attractive features of a relay is the LTE-based wireless backhaul as this could provide a simple way of improving coverage.

located close to but not admitted to connect to the home base station will be subject to strong interference, and may not be able to access the macrocell. In essence, the presence of a home base station may cause a coverage hole in the operator's macro network; a problem that is particularly worrisome as home base stations typically are user deployed, and their locations are not controlled by the operator. Similarly, reception at the home base station may be severely impacted by uplink transmissions from the terminal connected to the macrocell. Therefore, if closed subscriber groups are supported, it is preferable to use a separate carrier for the CSG cells to maintain the overall performance of the radio access network. Interference handling between CSG cells, which typically lack backhaul-based coordination schemes, could rely on distributed algorithms for power control and/or resource partitioning between the cells.

RELAYING

LTE Release 10 also extends the LTE radio access technology with support for *relaying functionality* (Fig. 4). With relaying, the mobile terminal communicates with the network via a *relay node* that is *wirelessly connected* to a *donor cell* using the LTE radio interface technology. The donor cell may, in addition to one or several relays, also directly serve terminals of its own. The donor-relay link may operate on the same frequency as the relay-terminal link (*inband relaying*) or on a different frequency (*outband relaying*). With the 3GPP relaying solution [6], the relay node will, from a terminal point of view, appear as an ordinary cell. This has the important advantage of simplifying the terminal implementation and making the relay node backward compatible (i.e., also accessible to LTE Release 8 terminals). In essence, the relay is a low-power base station wirelessly connected to the remaining part of the network. One of the attractive features of a relay is the LTE-based wireless backhaul as this could provide a simple way of improving coverage, e.g., in indoor environments by simply placing relays at the problematic locations. At a later stage, if motivated by the traffic situation, the wireless donor-relay link could be replaced by e.g., an optical fiber in order to use the precious radio resources in the donor cell for terminal communication instead of serving the relay.

Due to the relay transmitter causing interference to its own receiver, simultaneous donor-to-relay and relay-to-terminal transmission may not be feasible unless sufficient isolation of the outgoing and incoming signals is provided, for example, by means of specific well separated and well isolated antenna structures or through the use of outband relaying. Similarly, at the relay it may not be possible to receive transmissions from the terminals simultaneously with the relay transmitting to the donor cell. In Release 10 a *gap* in the relay-to-terminal transmissions to allow for reception of donor-to-relay transmissions is created using MBSFN subframes,[1] as shown in Fig. 4. In an MBSFN subframe the first one or two OFDM symbols in a subframe are transmitted as usual carrying cell-specific reference signals and downlink control signaling, while the rest of an MBSFN subframe is not used and can therefore be used for the donor-to-relay communication. The benefit of using MBSFN subframes compared to blanking transmission in the whole subframe is backward compatibility with Release 8/9 terminals. Blanking the whole subframe would not be compatible with Release 8/9 terminals as they assume cell-specific reference signals to be present in (part of) each subframe, while MBSFN subframes are supported already in Release 8. Similar to the downlink gaps obtained through the use of MBSFN subframes, there is a need to create gaps in the terminal-to-relay transmission in order for the relay to transmit to the donor. This is handled by not scheduling terminal-to-relay transmissions in some subframes.

[1] *Multicast-broadcast single-frequency network (MBSFN) subframes, present already in Release 8, were originally intended for broadcast support but has later been seen as a generic tool (e.g., to blank parts of a subframe for relaying support).*

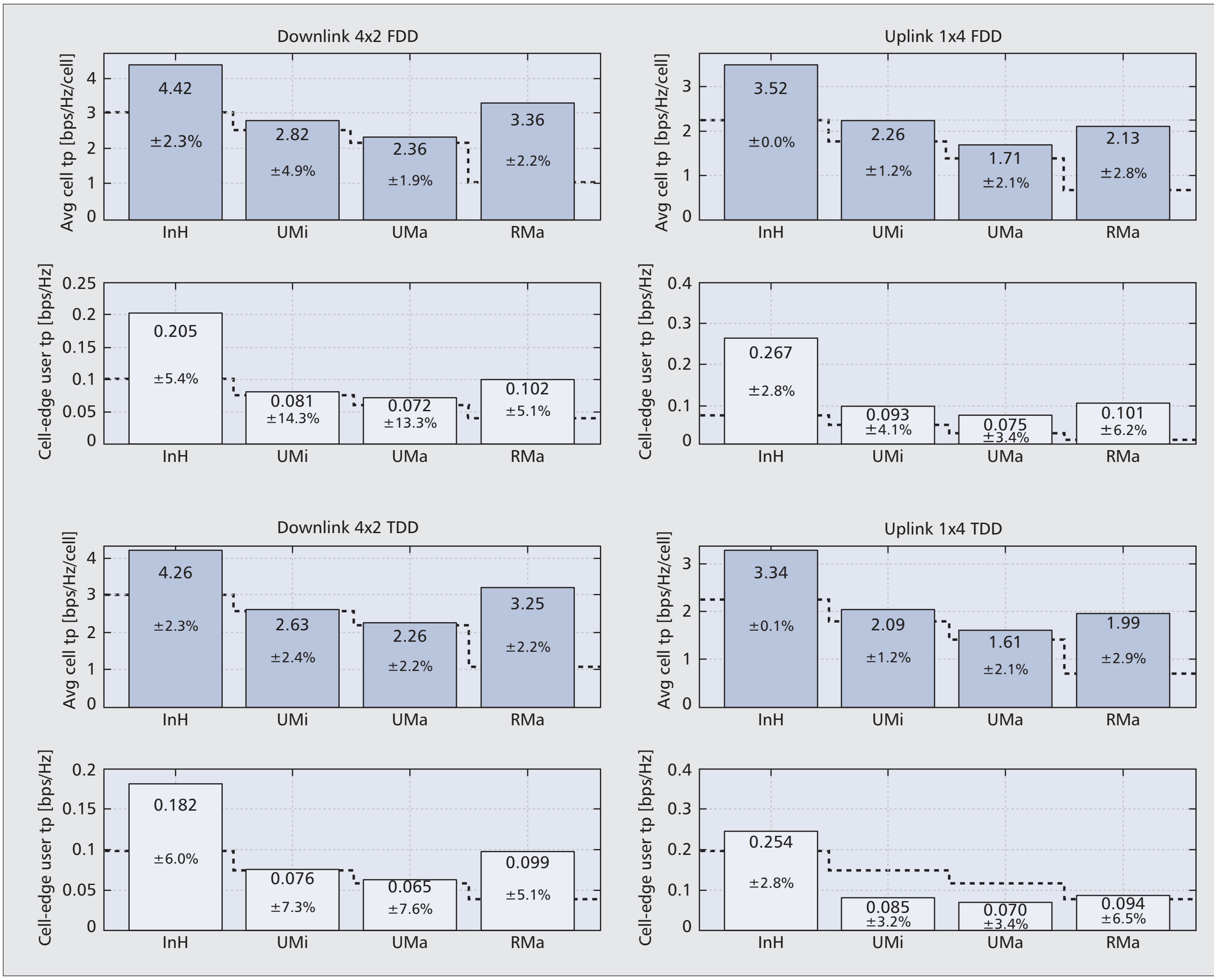

Figure 5. *Performance results for FDD (top) and TDD (bottom), and downlink (right) and uplink (left).*

Since the relay needs to transmit cell-specific reference signals in the first part of an MBSFN subframe, it cannot receive the normal control signaling from the donor cell. Therefore, Release 10 defines a new control channel, transmitted later in the subframe as shown in Fig. 4, to provide control signaling from the donor to the relay. This control channel type, of which multiple instances can be configured, carries downlink scheduling assignments and uplink scheduling grants in the same way as the normal control signaling. As the assignments refer to data in the same subframe and the grants relate to transmissions in a later subframe, early decoding of the former control information is beneficial. For this reason, downlink assignments are transmitted in the first part of the donor-to-relay transmission, while the latter part is used for (less time-critical) uplink grants.

Performance Results

As discussed in the introduction, ITU has defined basic requirements to be fulfilled by any IMT-Advanced technology [4]. Some of the most basic requirements, together with the corresponding capabilities of LTE [7], are summarized in Table 1.

From the table it is seen that already the first release of LTE, Release 8, is capable of meeting all of the requirements except the bandwidth and uplink spectral efficiency requirements. These two requirements are addressed in Release 10 through carrier aggregation and uplink spatial multiplexing, respectively.

For the detailed requirements on average and cell-edge spectral-efficiency, 3GPP has carried out an extensive evaluation campaign to conclude on the performance of the LTE radio-access technology in relation to the IMT-Advanced requirements. Examples of LTE system performance for the different test environments specified by the ITU (indoor hotspot, urban micro, urban macro, and rural) are provided in Fig. 5. In the downlink, a coordinated beamforming scheme is used with spatial multiplexing of two layers to a single terminal in each beam. Beams are dynamically adapted to limit interference, allowing reuse of time-frequency resources within cells. The beam-forming is coordinated between cells belonging to the same site. This can be seen as a simple form of coordinated multipoint transmission (CoMP) or multi-user MIMO. In the uplink, single-layer transmission is used. For further details on the simulation assumptions, please see [8]. These performance results are achieved without using any of the features introduced in Release 10. The IMT-Advanced requirements on average and cell edge spectral efficiency can thus already be fulfilled with LTE Release 8. It is important to point out that this does not mean that Release 10 features, such as extended downlink multi-antenna transmission and relaying functionality, are of no use. Rather, these features take the capabilities of the LTE radio access technology even further, beyond IMT-Advanced. Thus, by including more advanced features, such as extended multi-antenna transmission, LTE system performance is further enhanced, beyond what is illustrated above. A wider range of deployment scenarios is also addressed, including such with relays and non-contiguous spectrum allocations.

Conclusion

This article has provided a high-level overview of the evolution of LTE towards Release 10. Some of the key components — carrier aggregation, enhanced multi-antenna support, and relaying — are described. Numerical results show that LTE Release 10 fulfills and even surpasses the IMT-Advanced requirements. Given the large momentum behind LTE, this is a very attractive route for an operator to meet future demands on mobile broadband. Clearly, LTE is a very flexible platform and will continue to evolve for many years to come.

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Biographies

STEFAN PARKVALL [SM] (stefan.parkvall@ericsson.com) joined Ericsson Research in 1999 and is currently a principal researcher in the area of radio access, working with research and standardization of cellular technologies. He has been heavily involved in the development of HSPA and LTE and is also co-author of *3G Evolution: HSPA and LTE for Mobile Broadband*. In 2009 he received "Stora Teknikpriset" (one of Sweden's major technical awards) for his work on HSPA. He holds a Ph.D. from the Royal Institute of Technology (KTH), Stockholm, Sweden. His previous positions include assistant professor in communication theory at KTH and visiting researcher at the University of California, San Diego.

ANDERS FURUSKÄR is a principal researcher within the field of wireless access networks at Ericsson Research. His current focus is on evolving HSPA and LTE to meet future demands on data rates and traffic volumes. He holds an M.Sc. and a Ph.D. from KTH. He joined Ericsson in 1990.

ERIK DAHLMAN joined Ericsson Research in 1993 and is currently senior expert in the area of radio access technologies. He has been deeply involved in the development and standardization of 3G radio access technologies (WCDMA/HSPA) as well as LTE and its evolution. He is part of the Ericsson Research management team working with long-term radio access strategies. He is also co-author of the book *3G Evolution: HSPA and LTE for Mobile Broadband* and, together with Stefan Parkvall, received "Stora Teknikpriset" in 2009 for his contributions to the standardization of HSPA. He holds a Ph.D. from KTH.

Given the large momentum behind LTE, this is a very attractive route for an operator to meet future demands on mobile broadband. Clearly, LTE is a very flexible platform and will continue to evolve for many years to come.