Evolution of LTE towards IMT-Advanced

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Abstract

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

1 Introduction

Deployment of 4G mobile-broadband systems based on the highly flexible LTE radio-access technology [1][2] defined by 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 Rel-8, which was finalized in 2008. Rel-8 can provide downlink and uplink peak rates up to 300 Mbit/s and 75 Mbit/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 FDD and TDD, and targets a smooth evolution from earlier 3GPP technologies such as TD-SCDMA and WCDMA/HSPA as well as 3GPP2 technologies such as cdma2000.

The LTE radio-access technology is continuously evolving to meet future requirements. In Rel-9, finalized by 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 Rel-10, finalized at the end of 2010 and further extending the performance and capabilities of LTE beyond Rel-8/9. An important aim of LTE Rel-10 is to ensure that the LTE fulfills all the requirements for IMT-Advanced as defined by ITU [3][4]. The relation to IMT-Advanced is also the reason for the label “LTE-Advanced” sometimes given to LTE Rel-10 and beyond.

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

2 Overview of LTE Rel-8

LTE is an OFDM-based radio-access technology, with conventional OFDM on the downlink and DFT-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 ten subframes forming a radio frame as illustrated in Figure 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 Figure 1, cell-specific reference signals are also transmitted in each downlink subframe. These reference signals are used for data demodulation at the terminal (or 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 both frequency division duplex (FDD) and time division duplex (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 MIMO as well as multi-user MIMO) and beam-forming.

2.1 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 Rel-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 Rel-10 work, aimed *beyond* IMT-Advanced [5]. In 2010, 3GPP submitted LTE Rel-10 to ITU and, based upon this submission, ITU approved LTE Rel-10 as one of two IMT-Advanced technologies. As will be seen in Section 4, Rel-10 will not only fulfill the IMT-Advanced requirements but in many cases even surpass them.

3 LTE Rel-10

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

3.1 Carrier aggregation

Already the first release of LTE, Rel-8, provides extensive support for deployment in spectrum allocations of various characteristics, with bandwidths ranging from around 1.4 MHz up to 20 MHz in both paired and unpaired bands. In Rel-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 Figure 2. Up to five component carriers, possibly each of different bandwidth, can be aggregated allowing for transmission bandwidths up to 100 MHz. Backwards compatibility is catered for as each component carrier uses the Rel-8 structure. Hence, to a Rel-8/9 terminal each component carrier will appear as an LTE Rel-8 carrier, while a carrier-aggregation-capable terminal can exploit the total aggregated bandwidth enabling higher data rates. In the general case, different number 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 Figure 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 a wide overall bandwidth even though they do not posses a single wideband spectrum allocation. From a baseband perspective, there is no difference between the cases and they are all supported by LTE Rel-10. However, the 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 hereof is heterogeneous deployments as will be discussed below.

Scheduling and hybrid-ARQ retransmissions are handled independently for each component carrier, see Figure 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 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.

3.2 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* pre-coding, including the possibility for multi-layer transmission (spatial multiplexing) with up to four layers, is supported in LTE Rel-8. This includes the possibility for rank-adaptation down to *single-layer* transmission, leading to codebook-based *beam-forming*, 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 Rel-8 to support single-layer beam-forming; support that is extended to dual-layer transmission in Rel-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 beam-forming with more than four antennas and, for TDD, reciprocity-based transmission strategies.

In Rel-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, Rel-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 in 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 reducing the reference signal overhead, especially for high degrees of spatial multiplexing, and allows for implementation of various beam-forming schemes.

Uplink spatial multiplexing of up to four layers is also part of Rel-10. The basis is a codebook-based scheme where the scheduler in the base station determines the pre-coding matrix to be applied in the terminal. The selected pre-coding 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.

3.3 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, etc. 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 Figure 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 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 in LTE Rel-8/9. However, Rel-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 to, 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 non-trivial 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 (dashed in Figure 3) where downlink transmission from the low-power node to a terminal is subject to strong interference from the macro cell. The signal-to-interference 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 what is the case in a traditional homogeneous macro network.

For the data part of a subframe, this is not a serious problem as the *inter-cell interference coordination* (ICIC) mechanism present in LTE already from Rel-8 can be used. With ICIC, different cells can exchange information about which frequencies they intend to schedule transmissions upon in the near future, thereby reducing or completely avoiding inter-cell 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 Rel-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 Figure 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 macro cell. Since Rel-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 a 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 dashed area in Figure 3, will have the same peak data rates as in the case of a single 20 MHz carrier. Rel-8/9 can also benefit from seeing a ‘larger’ pico cell 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 Figure 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 backwards-compatibility reasons, 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, Rel-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. Note that in this approach, Rel-8/9 terminals will connect to the macro and not the low-power node in the dashed area in Figure 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* (CSG) is commonly used to refer to cases when access to such low-power base station is limited to a small set of terminals, e.g. the family living in the house where the home base station is located. CSG results in additional interference scenarios. For example, a terminal located close to but not admitted to connect to the home base station will be subject to strong interference may not be able to access the macro cell. 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 the home base stations typically are user deployed and their location 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 macro cell. 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.

3.4 Relaying

LTE Rel-10 also extends the LTE radio-access technology with support for *relaying functionality* (Figure 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 backwards compatible, i.e. accessible also to LTE Rel-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 e.g. 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 Rel-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 Figure 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 backwards compatibility with Rel-8/9 terminals. Blanking the whole subframe would not be compatible with Rel-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 Rel-8. Similarly 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.

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, Rel-10 defines a new control channel, transmitted later in the subframe as shown in Figure 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 while 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.

[1] MBSFN (Multicast-Broadcast Single Frequency Network) subframes, present already in Rel-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.

4 Performance Results

As discussed already 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 (from [7]), are summarized in Table 1.

From the table it is seen that already the first release of LTE, Rel-8, is capable of meeting all of the requirements except the bandwidth and uplink spectral efficiency requirements. These two requirements are addressed in Rel-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 Figure 5 below. In the downlink, a coordinated beam-forming scheme is used in the downlink 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 MU-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 Rel-10. The IMT-Advanced requirements on average and cell-edge spectral efficiency can thus be fulfilled already with LTE Rel-8. It is important to point out that this does not mean that Rel-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, including more advanced features, such as extended multi-antenna transmission, the 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.

5 Conclusion

This paper has provided a high-level overview of the evolution of LTE towards Rel-10. Some of the key components – carrier aggregation, enhanced multi-antenna support, and relaying – were described. Numerical results show that LTE Rel-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.

6 References

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[8] A. Furuskär, "Performance Evaluations of LTE-Advanced – The 3GPP ITU proposal", The 12th International Symposium on Wireless Personal Multimedia Communications (WPMC2009), Sendai, Japan, Sep. 2009.

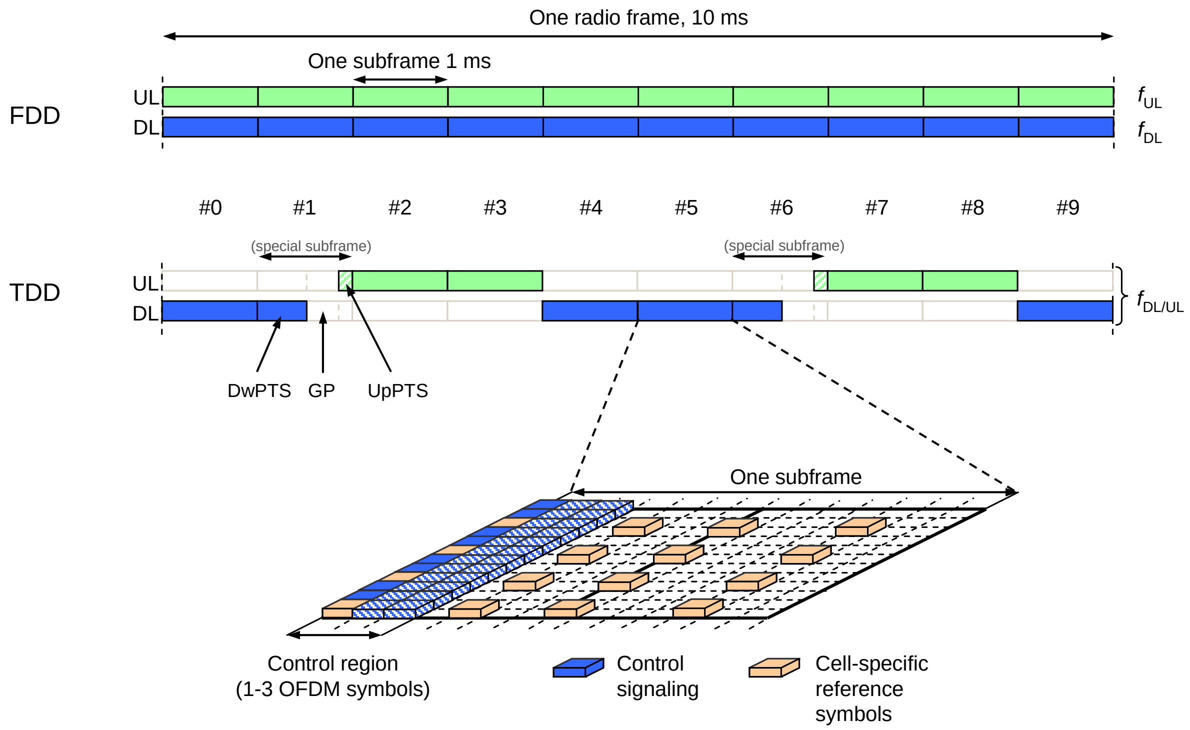

Figure 1: LTE time-frequency structure.

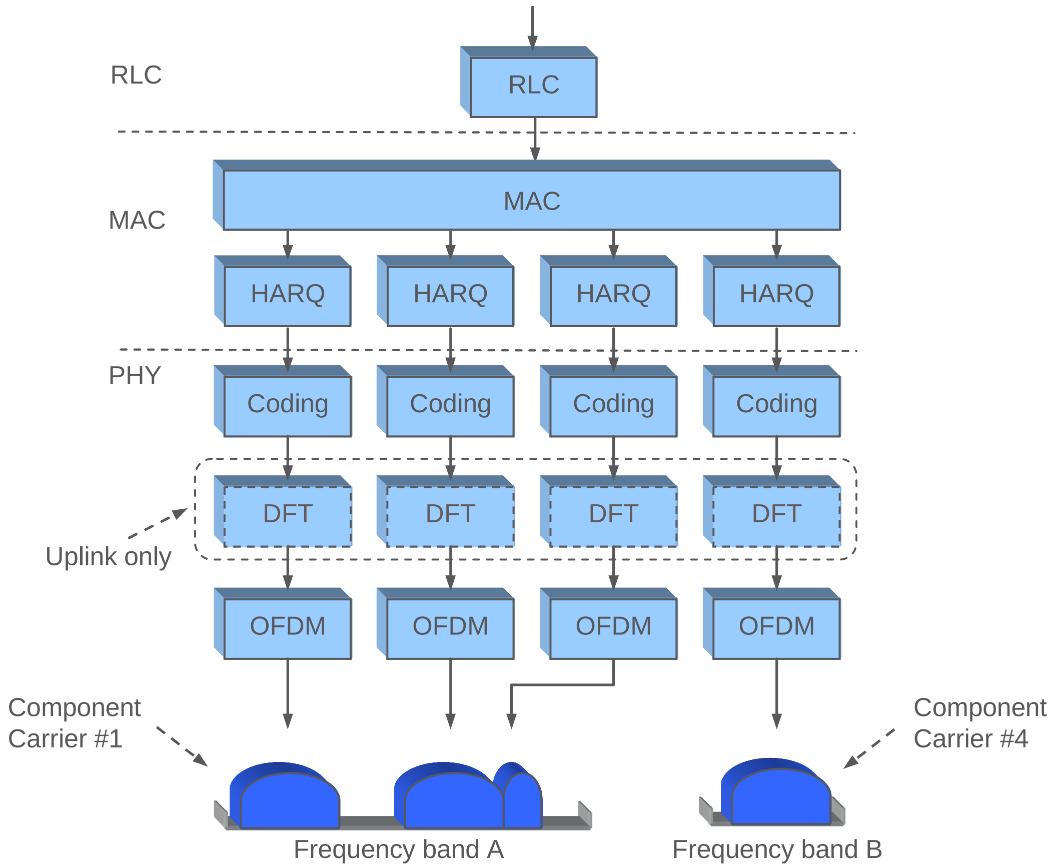

Figure 2: Carrier aggregation in LTE Rel-10.

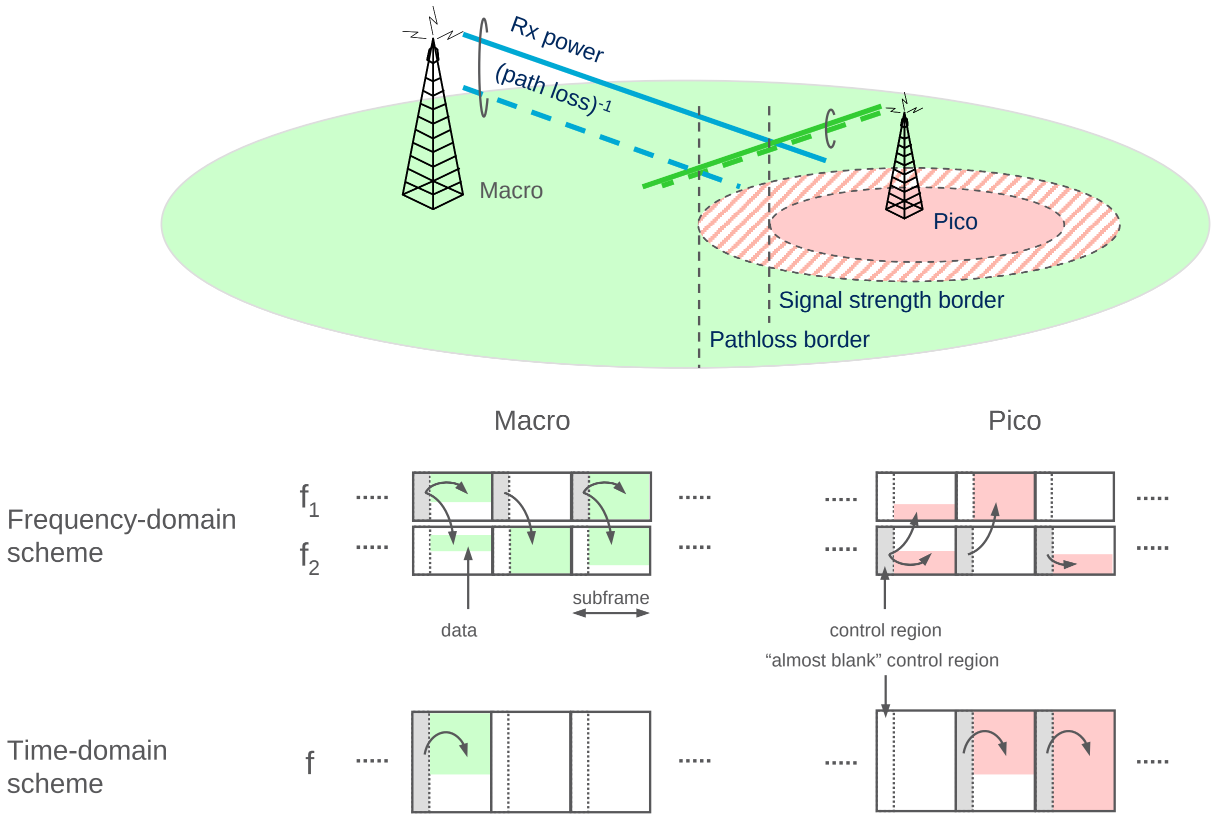

Figure 3: Heterogeneous deployment with a macro cell overlaying multiple pico cells.

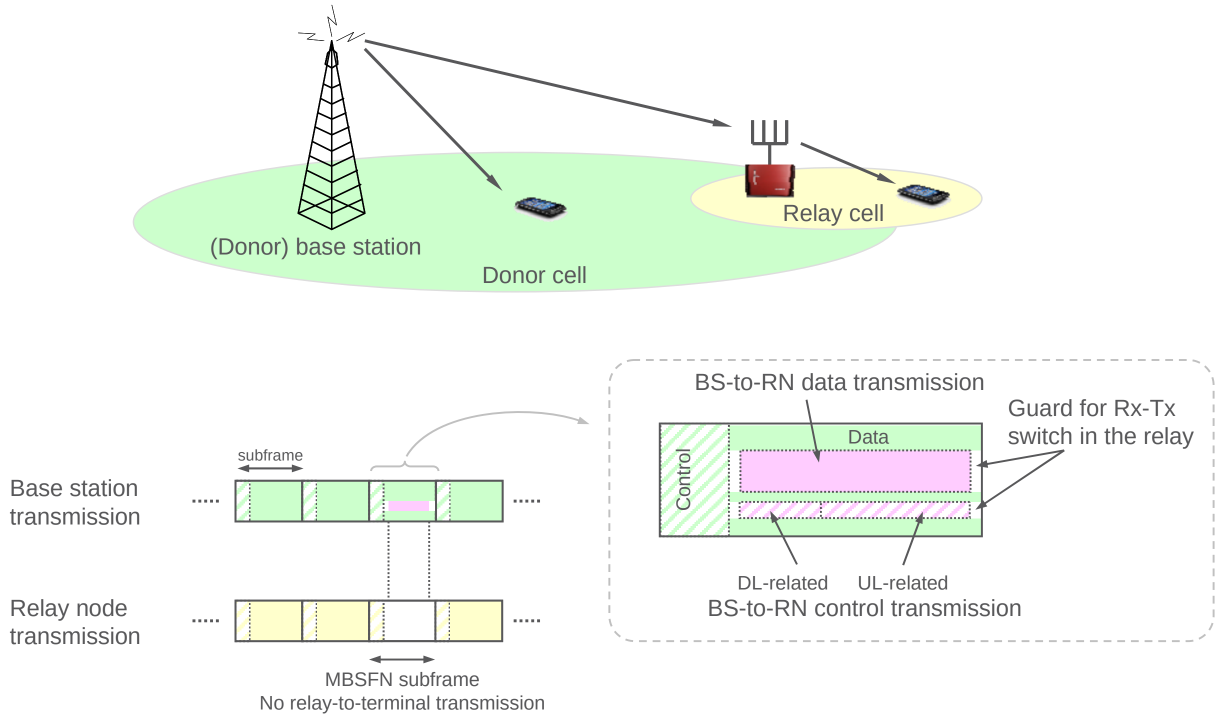

Figure 4: Relaying.

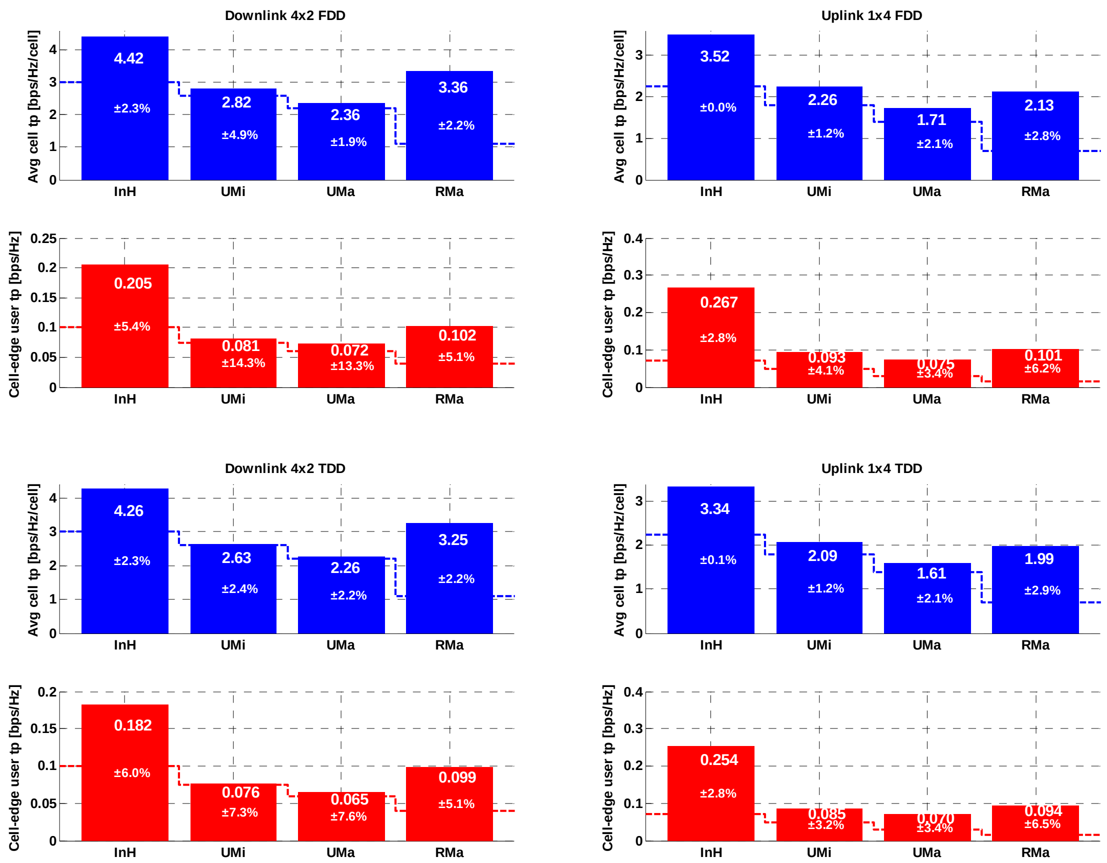

Figure 5: Performance results for FDD (top) and TDD (bottom), and downlink (right) and uplink (left).

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

* Value is for a 4x4 antenna configuration. Value in parentheses for 8x8
** Values is for a 2x2 antenna configuration. Value in parentheses for 4x4

Table 1: Requirements and LTE fulfillment.

Biographies

Stefan Parkvall (senior member, IEEE) 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. Dr Parkvall holds a Ph.D. from the Royal Institute of Technology (KTH), Stockholm Sweden in 1996. His previous positions include assistant professor in communication theory at the Royal Institute of Technology, Stockholm, Sweden, and a visiting researcher at University of California, San Diego, USA.

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. Dr Furuskär holds an MSc and a PhD from the Royal Institute of Technology in Stockholm. 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. Dr Dahlman 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 PhD from the Royal Institute of Technology in Stockholm.