LTE: The Evolution of Mobile Broadband

David Astély, Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindström, and Stefan Parkvall, Ericsson Research

ABSTRACT

This article provides an overview of the LTE radio interface, recently approved by the 3GPP, together with a more in-depth description of its features such as spectrum flexibility, multi-antenna transmission, and inter-cell interference control. The performance of LTE and some of its key features is illustrated with simulation results. The article is concluded with an outlook into the future evolution of LTE.

INTRODUCTION

The long-term evolution (LTE) as defined by the 3rd Generation Partnership Project (3GPP) is a highly flexible radio interface [1, 2]; its initial deployment is expected by the end of 2009. The first release of LTE provides peak rates of 300 Mb/s, a radio-network delay of less than 5 ms, a significant increase in spectrum efficiency compared to previous cellular systems, and a new flat radio-network architecture designed to simplify operation and to reduce cost. LTE supports both frequency-division duplex (FDD) and time-division duplex (TDD), as well as a wide range of system bandwidths in order to operate in a large number of different spectrum allocations. Furthermore, LTE also aims for a smooth evolution from earlier 3GPP systems such as time division-synchronous code division multiple access (TD-SCDMA) and wide-band code division multiple access/high-speed packet access (WCDMA/HSPA), as well as 3GPP2 systems such as code division multiple access (cdma)2000. Finally, LTE also constitutes a major step toward international mobile telephony (IMT)-Advanced. In fact, the first release of LTE already includes many of the features originally considered for future fourth-generation systems [3].

For an in-depth description of LTE, the reader is referred to [1]. A companion article [4] in this issue discusses the link-layer design. In this article, we provide an overview of the first release of LTE, release-8. The basic transmission schemes in uplink and downlink are described, and various aspects of LTE, such as spectrum flexibility, multiple-antenna transmission, and inter-cell interference coordination are discussed. This is followed by a set of simulation results, exemplifying the performance of LTE. Finally, we offer a short overview of the current, ongoing work on the evolution of LTE toward LTE-Advanced and the full IMT-Advanced capability.

LTE: AN OVERVIEW

BASIC TRANSMISSION SCHEME

Orthogonal frequency-division multiplexing (OFDM), with data transmitted on a large number of parallel, narrow-band subcarriers, is the core of the LTE downlink radio transmission. Due to the use of relatively narrowband subcarriers in combination with a cyclic prefix, OFDM transmission is inherently robust to time dispersion on the radio channel without a requirement to resort to advanced and potentially complex receiver-side channel equalization. For the downlink, this is an attractive property because it simplifies the receiver baseband processing with reduced terminal cost and power consumption as consequences. This is especially important considering the wide transmission bandwidths of LTE, and even more so in combination with advanced multi-antenna transmission, such as spatial multiplexing (discussed below in this section).

For the uplink, where the available transmission power is significantly lower than for the downlink, the situation is somewhat different. Rather than the amount of processing power at the receiver, one of the most important factors in the uplink design is to enable highly *power-efficient* transmission. This improves coverage and reduces terminal cost and power consumption at the transmitter. For this reason, *single-carrier* transmission, based on *discrete Fourier transform (DFT)-precoded OFDM*, sometimes also referred to as *single-carrier frequency-division multiple access (SC-FDMA)*, is used for the LTE uplink. DFT-precoded OFDM has a smaller peak-to-average power ratio than regular OFDM, thus enabling less complex and/or higher-power terminals.

The basic protocol structure of LTE is illustrated in Fig. 1. The radio link control (RLC) and medium access control (MAC) layers, among other tasks, are responsible for retransmission handling and multiplexing of data flows. In the physical layer, the data that is to be transmitted is turbo coded and modulated using one of the following: quadrature-phase shift keying (QPSK), 16-QAM, or 64-QAM, followed by OFDM modulation. The subcarrier spacing is 15 kHz and two cyclic-prefix lengths are supported in both uplink and downlink, a normal cyclic prefix of 4.7 µs, suitable for most deployments and an extended

 0163-6804/09/$25.00 © 2009 IEEE

cyclic prefix of 16.7 μs for highly dispersive environments. In the downlink, different types of multi-antenna processing, further described below, are applied prior to OFDM modulation. In the uplink, to preserve the single-carrier properties, a DFT precoder is used prior to the OFDM modulator. Note that the DFT precoder does not compromise orthogonality between subcarriers. To support channel estimation for coherent demodulation, as well as for various measurement purposes, including not only measurements for mobility management but also channel quality measurements, cell-specific reference signals are transmitted in the downlink.

The transmitted signal is organized into subframes of 1-ms duration, each consisting of 14 or 12 OFDM symbols, depending on whether normal or extended cyclic prefix is used. Ten subframes form a radio frame as shown in Fig. 2. The short subframe duration of 1 ms results in small delays, not only for user data, but also for control signaling such as the hybrid automatic repeat-reQuest (ARQ) feedback and channel-quality feedback from the terminals to the base station.

As illustrated in Fig. 2, LTE supports FDD, as well as TDD, the latter commonly referred to as TD-LTE. Although the time-domain structure is, in most respects, the same for both duplexing schemes, there are some differences between the two, most notably the presence of a special subframe in TD-LTE to provide the required guard time for downlink-to-uplink switching as further elaborated below.

An intrinsic characteristic of radio communication is fading, which results in the instantaneous radio-channel quality varying in time, space, and frequency. Due to the use of OFDM-based transmission, LTE can use *channel-dependent scheduling* in both the time and frequency domain to exploit rather than suppress such rapid channel-quality variations, thereby achieving more efficient utilization of the available radio resources. This is illustrated in Fig. 3. The scheduler determines, for each 1 ms subframe, which users(s) are allowed to transmit, on what frequency resources the transmission is to take place, and what data rate to use. The short subframe duration of 1 ms allows relatively fast channel variations to be tracked and utilized by the scheduler. In the frequency domain, the scheduling granularity is 180 kHz. Note that both the downlink and uplink transmissions are controlled by the scheduler located in the base station. The scheduler is thus a key element and to a large extent determines the overall downlink system performance, especially in a highly loaded network. To aid the downlink scheduler in its decision, the instantaneous channel-quality at the terminals is estimated and fed back to the base station, possibly as often as once per subframe. In the uplink, the terminals can be configured to transmit a sounding reference signal, the reception quality of which may be used for uplink channel-dependent scheduling.

To handle occasional retransmission errors, LTE includes a two-layered retransmission scheme: a fast hybrid-ARQ protocol with low overhead feedback and support for soft combining with incremental redundancy is complemented by a highly reliable selective-repeat ARQ protocol. This can be seen in Fig. 1 with hybrid-ARQ located in the MAC layer and ARQ in the RLC layer. The use of a two-layered mechanism achieves low latency and low overhead without sacrificing reliability. Most errors are captured and corrected by the lightweight hybrid-ARQ protocol, which provides feedback to the transmitter for each transmitted subframe; only rarely, in terms of latency and overhead, the more expensive ARQ retransmissions are required. The tight coupling between the two retransmission layers is possible because both mechanisms are terminated in the base station.

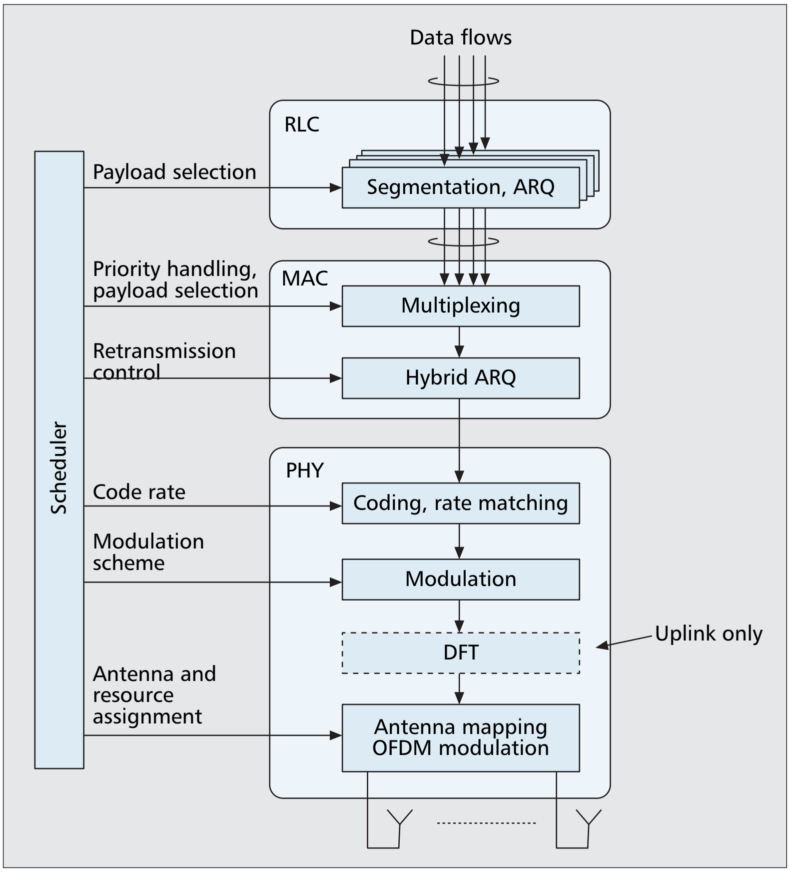
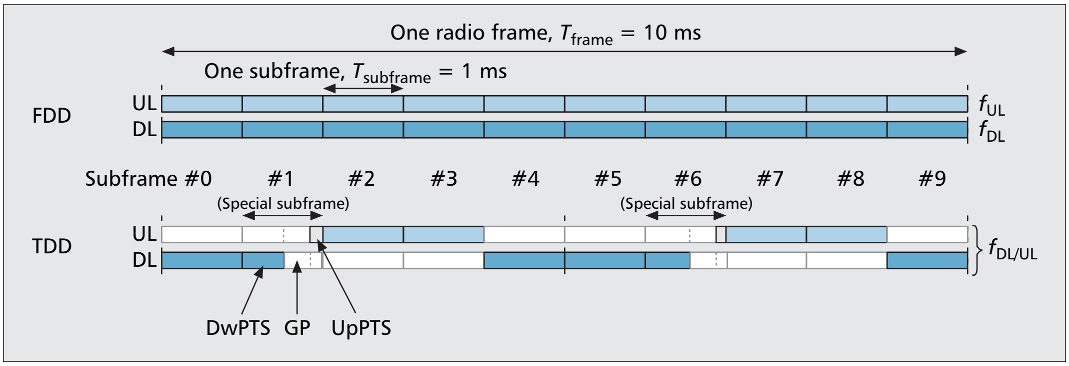


Figure 1. *LTE protocol structure (simplified).*

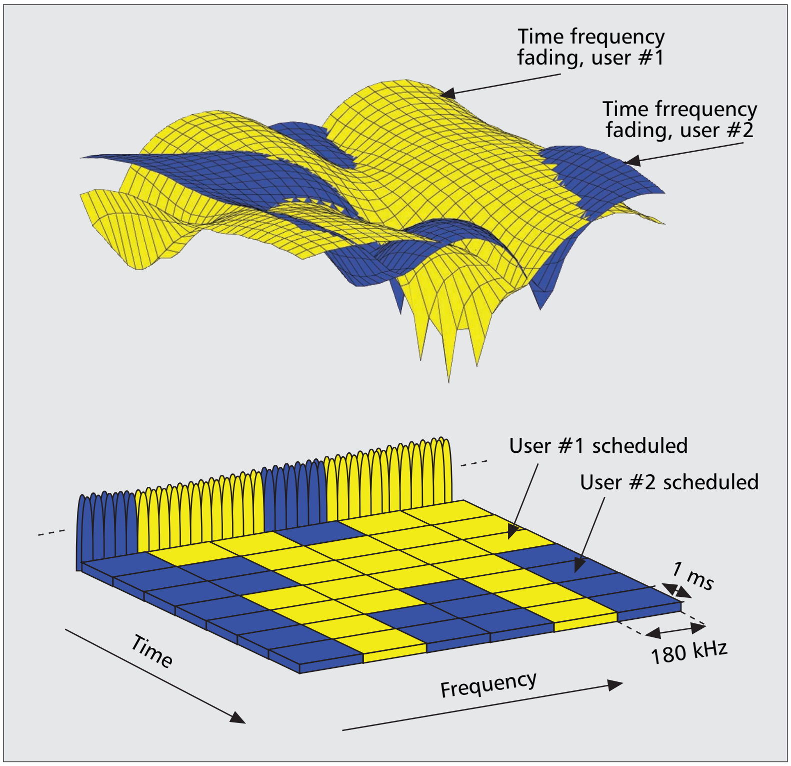
To support the LTE features, scheduling decisions, hybrid-ARQ feedback, channel-status reports, and other control information must be communicated between the base station and the terminal. In the downlink, the control signaling is transmitted using (typically) up to three of the first OFDM symbols in each subframe. The code rate of the control signaling for each terminal can be adjusted individually to match the instantaneous channel conditions and to minimize the overhead. Also, the total amount of resources in the downlink used for control signaling can be varied dynamically to minimize the overhead.

Spectrum Flexibility — Transmission Bandwidth

Depending on regulatory aspects in different geographical areas, radio spectrum for mobile communication is available in different frequency bands of different sizes and comes as both



■ **Figure 2.** *LTE frame structure.*



■ **Figure 3.** *Channel-quality variations in frequency and time.*

paired and *unpaired* bands. Paired frequency bands implies that uplink and downlink transmissions are assigned separate frequency bands, whereas in the case of unpaired frequency bands, uplink and downlink must share the same frequency band. Also, at least in an initial migration phase, different radio-access technologies often must be able to operate jointly in the same spectrum band. Spectrum flexibility, enabling operation under all these conditions, is one key feature of the LTE radio access.

LTE is able to operate not only in different frequency bands, but it also can be deployed with different bandwidths in order to operate in spectrum of different sizes, as well as to enable efficient migration of other radio-access technologies to LTE. More specifically, as illustrated in Fig. 4, LTE allows for an overall system bandwidth ranging from as small as 1.4 MHz up to 20 MHz, where the later is required to provide the highest LTE data rates. All terminals support the widest bandwidth. Unlike previous cellular systems, LTE provides the possibility for different uplink and downlink bandwidths, enabling asymmetric spectrum utilization.

To enable a terminal to access a cell prior to knowing the cell bandwidth and the duplexing scheme, the system information occupies only the most narrow bandwidth supported by LTE and is located in subframes guaranteed to be downlink subframes. After the terminal acquires the system information, the cell bandwidth and the duplexing scheme is known, and the terminal can access the cell based on this knowledge.

Spectrum Flexibility — Duplex Scheme

An important part of spectrum flexibility, as previously mentioned, is the possibility to operate in paired, as well as unpaired, spectrum allocations. Support for paired and unpaired spectrum is in itself not new to 3GPP. However, in the past this has been accomplished through different 3G radio-interface specifications: WCDMA for FDD and TD-SCDMA, as well as TD-CDMA for TDD, resulting in dual-mode terminals being relatively uncommon so far. Therefore, a strong requirement [5] of the LTE design was to provide a *single* radio interface supporting both FDD and TDD to provide an even larger economy-of-scale benefit to both duplex schemes.

Virtually all of the physical-layer processing is identical for FDD and TDD, enabling low-cost implementation of terminals supporting both the FDD and TDD modes of operation. The difference between the two is mainly in the frame structure as illustrated in Fig. 2.

- In the case of FDD operation (upper part of Fig. 2), there are two carrier frequencies, one for uplink transmission (f_{UL}) and one for downlink transmission (f_{DL}). Thus, during each frame, there are ten uplink subframes and ten downlink subframes; and uplink and downlink transmission can occur simultaneously within a cell. Inherently there is a one-to-one relation between downlink and uplink subframes, which is exploited in the control-signaling design.
- In the case of TDD operation (lower part of Fig. 2), there is only a single-carrier frequency, and uplink and downlink transmissions always are separated in time, also on a cell basis. To meet different requirements on uplink-downlink traffic asymmetries, seven different uplink-downlink configurations are

supported in TDD, providing downlink-uplink periodicities of 5 ms or 10 ms and downlink-to-uplink ratios from 2:3 to 9:1. As the number of uplink and downlink subframes in a radio frame can differ, there is no inherent one-to-one relation between downlink and uplink subframes, resulting in some minor differences in the control-signaling design between FDD and TDD.

An essential part of any TDD system is the provisioning of sufficiently large *guard periods* during which equipment can switch between transmission and reception with no overlap of signals to be transmitted and received. In LTE, guard periods are created by splitting one or two subframes, referred to as *special subframes*, in each radio frame into three fields: a downlink part (DwPTS), a guard period (GP), and an uplink part (UpPTS).

The downlink part of the special subframe (DwPTS) can be viewed as an ordinary, albeit shorter, downlink subframe and is used for downlink data transmission. Its length can be varied from three up to twelve OFDM symbols. Unlike normal subframes, where the control region can span up to three OFDM symbols, the maximum control region in DwPTS is two OFDM symbols. The reason is the location of the primary synchronization signal in the third OFDM symbol of the DwPTS in the case of TDD operation. On the other hand, for FDD the synchronization signal is located in the middle of subframe zero and five. The difference in synchronization-signal location enables the terminals to detect the duplex of the cell already at initial synchronization to a carrier.

The uplink part of the special subframe (UpPTS) has a short duration, one or two OFDM symbols, and can be used for transmission of uplink sounding-reference signals and random access. Sounding-reference signals are known signals, transmitted from the terminals and enabling the base station to estimate uplink channel-quality, for example, for the purpose of uplink channel-dependent scheduling and link adaptation. In addition to the UpPTS, uplink-channel sounding also can use the normal subframes in the same manner as in FDD. Random access typically uses one of the normal subframes as in FDD, enabling a relatively long random-access preamble to also provide coverage and capacity in large cells. However, in scenarios where random-access coverage is not an issue, a short random-access preamble in the UpPTS can be used instead.

The remaining symbols in the special subframe, which have not been allocated to DwPTS or UpPTS, are used to provide the guard period for the downlink-to-uplink and the uplink-to-downlink switch. The length of the guard period depends on several factors. First, the guard period must be sufficiently long to handle the propagation delay in the cells. To be time aligned at the base stations, terminals closer to the cell edge must start their transmission earlier in time than those close to the base stations. Obviously, the transmission at a cell-edge terminal cannot start until the downlink has been received completely. Hence, the guard period must cover the maximum roundtrip propagation delay within the cell in addition to the time it takes for a terminal to switch from reception to transmission. In addition, the guard time also must be selected by taking base-station-to-base-station interference into account. Due to the propagation delay, a downlink transmission from a distant base station is still “in the air” at the base station trying to receive uplink transmissions even though all base stations switched from downlink to uplink at the same time. With the DwPTS and UpPTS durations mentioned above, LTE supports a guard period ranging from two to ten OFDM symbols (140–667 μs), sufficient for cell sizes up to and beyond 100 km.

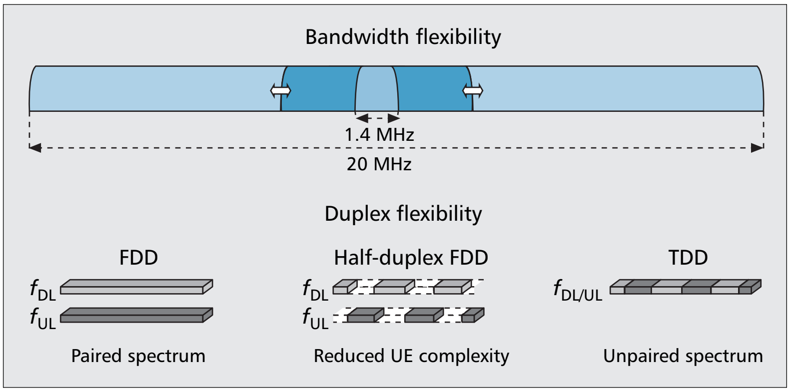


Figure 4. *LTE spectrum (bandwidth and duplex) flexibility. Half duplex FDD is seen from a terminal perspective.*

Supporting multiple configurations of the special subframe is useful not only to support different cell sizes and propagation conditions as discussed above, but also to support coexistence between LTE and other, already deployed TDD systems, most notably TD-SCDMA [5]. To avoid inter-system interference (without resorting to expensive filtering of large guard bands), uplink and downlink transmissions in LTE and TD-SCDMA should be mutually aligned, that is, the downlink-uplink switch-points should coincide between the two systems. The subframe duration of LTE and the universal terrestrial radio access (UTRA) TDD technologies TD-SCDMA and TD-CDMA are 1 ms, 0.675 ms, and 0.667 ms, respectively, making such an alignment challenging. However, the use of the special subframe in LTE offers an elegant solution to this problem. By selecting the appropriate length of the DwPTS and UpPTS, switch-point alignment between LTE-TDD and TD-SCDMA (and other TDD-based radio-access schemes) can be achieved. In fact, coexistence with TD-SCDMA was one of the main technical reasons for the introduction of the special subframes.

Multi-Antenna Transmission

Support for multi-antenna transmission was an integral part of LTE from the first release, and the channel quality measurements for link adaptation and scheduling are designed to cater to this. The fact that the performance requirements are set, assuming all terminals support at least two receive antennas, is important because it enables the networks to be planned, assuming at least the presence of downlink-receive diversity. More advanced multi-antenna schemes also are supported by LTE, including transmit diversity, spatial multiplexing (including both so-called single-user multi-

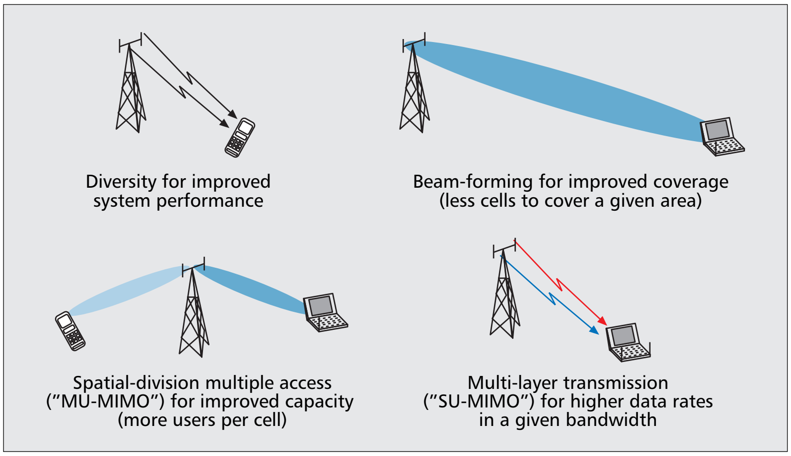


Figure 5. *Multiple-antenna techniques in LTE.*

ple-input multiple-output [MIMO], as well as multi-user MIMO) with up to four antennas, and beamforming. Which of the schemes (or which combination of the schemes) to use depends on the scenario (Fig. 5). In the uplink, both open- and closed-loop transmit-antenna selection are supported as optional features.

LTE transmit diversity is based on so-called space-frequency block coding (SFBC), complemented with frequency-switched transmit diversity (FSTD) in the case of four transmit antennas [1]. Transmit diversity is primarily intended for common downlink channels to provide additional diversity for transmissions for which channel-dependent scheduling is not possible. However, transmit diversity also can be applied to user-data transmission, for example, to voice-over-IP (VoIP), where the relatively low user-data rates may not justify the additional overhead associated with channel-dependent scheduling.

In case of *spatial multiplexing*, multiple antennas at both the transmitter (base station) *and* the receiver (terminal) side are used to provide *simultaneous* transmission of multiple, parallel data streams, also known as *layers*, over a single radio link, thereby significantly increasing the peak data rates that can be provided over the radio link. As an example, with four base-station transmit antennas and a corresponding set of (at least) four receive antennas at the terminal side, up to four data streams can be transmitted in parallel over the same radio link, effectively increasing the data rate by a factor of four.

LTE multi-stream transmission is *pre-coder* based. 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 performed and reported by the terminal, also known as *closed-loop spatial multiplexing*.

In the 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) *beamforming* function. More specifically, this type of beamforming can be referred to as *codebook-based* beamforming as the beamforming can be done only according to a limited set of pre-defined beamforming (precoder) vectors.

In addition to the codebook-based beamforming as a special case of the LTE spatial multiplexing, LTE also supports more general *non-codebook-based beamforming*. In contrast to codebook-based beamforming, in the case of non-codebook-based beamforming, the terminal must make an estimate of the overall beamformed channel. To enable this, LTE provides the possibility for the transmission of user equipment (UE)-specific reference symbols, transmitted using the same beamforming as the user data, and enabled for the terminal to estimate the overall beamformed channel.

Power Control and Inter-Cell Interference Coordination

LTE provides (intra-cell) orthogonality between users in both uplink and downlink, that is, at least in the ideal case, no interference between transmissions within the same cell but only interference between cells. Hence, LTE performance in terms of spectrum efficiency and available data rates is, relatively speaking, more limited by interference from other cells (inter-cell interference) compared to WCDMA/HSPA, especially for users at the cell edge. Therefore, the means to reduce or control the inter-cell interference potentially can provide substantial benefits to LTE performance, especially in terms of the service (data rates, etc.) that can be provided to users at the cell edge.

Uplink power control is one of the mechanisms in LTE used for this purpose. It is used to control not only the received signal strength in the intended cell, but also to control the amount of interference in neighboring cells. LTE uplink-power control supports *fractional path-loss compensation*, implying that users close to the cell border use relatively less transmit power, and thus generate relatively less interference to neighbor cells. However, LTE provides more advanced interference-handling schemes as well.

Inter-cell interference coordination (ICIC) is in essence a scheduling strategy used to limit the inter-cell interference. A simple method to improve cell-edge data rates is to restrict the usage of parts of the bandwidth statically, for example, through a reuse larger than one. Such schemes improve the signal-to-interference ratios of the used frequencies. However, the loss due to reduced bandwidth availability is typically larger than the corresponding gain due to higher signal-to-interference ratio, leading to an overall loss of efficiency. Therefore, the LTE standard provides tools for dynamic inter-cell-interference coordination of the scheduling in neighbor cells such that cell-edge users in different cells preferably are scheduled on complementary parts of the spectrum when required. Note that a major difference from static reuse schemes is that LTE still allows for the total available spectrum to be used in all cells. Bandwidth restrictions are applied only when motivated by traffic and radio conditions.

Interference coordination can be applied to both uplink and downlink, although with some fundamental differences between the two links. In the uplink, the interference originates from several geographically separated terminals, and thus, the overall interference varies over time with the scheduling decisions. On the other hand, in the downlink, the interference originates from the stationary base stations. Hence, the observed interference depends more heavily on the scheduling decision in the uplink case, compared to the downlink case, and it could be argued that inter-cell interference coordination can be more suited to the uplink. Also, as the LTE interference-coordination mechanism is based on scheduling restrictions in the frequency domain, it is suited mainly for relatively narrowband services not requiring the full system bandwidth. As the uplink transmission power generally is significantly smaller than the downlink transmission power, uplink transmissions tend to be more narrowband in nature than downlink transmissions. Also, this indicates that inter-cell-interference coordination tends to find its main application in the uplink.

To aid uplink inter-cell coordination, LTE defines two indicators exchanged between base stations: the *high-interference indicator* and the *overload indicator*.

The high-interference indicator provides information to neighboring cells about the part of the cell bandwidth upon which the cell intends to schedule its cell-edge users. Because cell-edge users are susceptible to inter-cell interference, upon receiving the high-interference indicator, a cell might want to avoid scheduling certain subsets of its own users on this part of the bandwidth. This subset includes users close to the cell that issues the high-interference indicator.

The overload indicator provides information on the uplink interference level experienced in each part of the cell bandwidth. A cell receiving the overload indicator may reduce the interference generated on some of these resource blocks by adjusting its scheduling strategy, for example, by using a different set of resources, and in this way, improve the interference situation for the neighbor cell that issues the overload indicator.

In the downlink, inter-cell coordination implies restrictions of the transmission power in some parts of the transmission bandwidth. In principle, this parameter could be configured on a static basis; however, as mentioned above, this is not very efficient. Instead dynamic, downlink coordination is supported through the definition of a *relative narrowband transmission-power indicator*. A cell can provide this information to neighboring cells, indicating the part of the bandwidth where it intends to limit the transmission power. A cell receiving the indication can schedule its downlink transmissions within this band, reducing the output power or completely freeing the resources on complementary parts of the spectrum. A crucial part of the supported inter-cell-interference coordination scheme in LTE is that full-frequency reuse in neighboring cells is possible.

Both uplink and downlink inter-cell-interference coordination strategies benefit from knowledge about the radio-wise position of a terminal relative to neighbor cells. For example, such knowledge can be obtained from the terminals measuring the signal strength from different cells, measurements that are required for mobility purposes in any case.

PERFORMANCE EVALUATION

To illustrate the LTE spectrum efficiency, a set of simulations was performed. To assess the benefits of some of the key features discussed above, the individual performance gains enabled by those features also are evaluated. This is accomplished by comparing the LTE FDD performance with a reference FDD system using more conventional techniques in the areas of multi-antennas transmission, scheduling, power control, and control channel design (represented by overhead and feedback delays). The characteristics of the reference system, as well as of the LTE system are listed in Table 1.

In general, system performance depends on the scenario, models, and assumptions used in the evaluations. In this study, these are aligned with the recommendations from next-generation mobile networks (NGMN) [6], which in turn are aligned with the 3GPP. In short, an urban environment, 500 m inter-site distance, indoor terminals, 2 GHz frequency band, and 10 MHz bandwidth are assumed. More details are listed in Table 1. Figure 6 shows spectrum efficiency results for downlink and uplink. The LTE spectrum efficiencies are illustrated by the uppermost bars. In both directions, the achieved spectrum efficiency well exceeds the target 1.53 bit/s/Hz/sector in downlink and 0.66 bit/s/Hz/sector in uplink set by the 3GPP at the start of the LTE design [5]. Also, the more difficult uplink requirement of 0.99 bit/s/Hz/sector set by the NGMN [7] is reached. The individual impact of the features, in the simulations assessed by replacing the LTE functionality with the corresponding simpler functionality, is shown in the lower bars. The percentage figure to the left represents the individual feature impact, and the percentage figure to the right represents the accumulated impact of the features combined. As an example, the lowest bar in the left part of Fig. 6 represents a system without several of the LTE features. This example system uses simpler scheduling, has a larger channel-quality-indicator (CQI) delay and a larger control-channel overhead, and does not use MIMO, resulting in a spectral efficiency of 1.07 bit/s/Hz/sector, that is, a spectral efficiency loss of 38 percent of which the absence of MIMO accounts for 6 percent. Note that without the key features, the targets would not have been reached.

The uppermost bars also include TD-LTE spectrum efficiencies. For TDD, the spectrum efficiency is normalized by downscaling the system bandwidth with the relative time utilization (for data symbols) in the direction in question. It is seen that in both downlink and uplink, the normalized FDD and TDD performance is indeed similar. The differences are due to the TDD guard period, the UpPTS, and the slightly longer channel-quality-feedback delays for TDD.

LTE-ADVANCED — LTE EVOLUTION TOWARD IMT-ADVANCED

As the work on the first release of LTE approaches its completion, activities on the further evolution of LTE are beginning to take shape within

LTE provides (intra-cell) orthogonality between users in both uplink and downlink, that is, at least in the ideal case, no interference between transmissions within the same cell but only interference between cells.

System Models	
Scheduler	LTE: DL: Proportional fair in time and frequency, UL: Quality-based FDM Reference: DL: Proportional fair in time, UL: FDM
MIMO	LTE: Codebook-based pre-coded adaptive rank MIMO Reference: Dynamic switching between spatial multiplexing MIMO and STC
Power control	LTE: Open loop with fractional pathloss compensation (α = 0.8), SNR target 10 dB at cell edge Reference: Open loop with full pathloss compensation (α = 1.0), SNR target 15 dB
Overhead	LTE: Based on LTE specification and NGMN assumptions Reference: Estimation of overhead with joint coding (non-user-adaptive), UL reference signals supporting distributed allocation
TDD asymmetry	DL: 2 subframes + 12 symbols DwPTS, UL: 2 subframes + 1 symbol UpPTS, GP: 1 symbol
CQI delay	LTE: Corresponding to 1 ms subframes Reference: Corresponding to 5 ms subframes
BS/Terminal power	46 dBm/23 dBm
Antenna configurations	BS: 2 transmit and receive; Terminal: 1 transmit, 2 receive
Receiver type	MMSE, with SIC in DL
User Behavior Models	
Traffic Model	Full buffer (10 users per sector)
User location	Uniform distribution
Terminal speed	3 km/h
Radio Network Models	
Site-to-site distance	500 m
Carrier frequency	2.0 GHz
Carrier bandwidth	10 MHz
Distance-dependent pathloss	$L = I + 37.6 \cdot \log_{10}(R) + P$, R in km, I = 128.1 for 2 GHz, P = 20 dB penetration loss
Lognormal shadowing	8 dB std dev, 50 m correlation distance, 0.5 correlation between sites
Channel model	3GPP SCM, extended to 10MHz

Table 1. *Models and assumptions.*

the 3GPP. In April 2008, the study item, "Requirements for Further Advancements for E-UTRA," often referred to as "LTE-Advanced," was initiated. The aim of "LTE-Advanced" is to further enhance LTE radio access in terms of system performance and capabilities [8], with a specific goal to ensure that LTE fulfills all requirements of "IMT-Advanced" as defined by the International Telecommunication Union [9].

At the time of this writing, the work on LTE-Advanced within the 3GPP is still in an early phase with several technology components being discussed. These components include:

- *Carrier aggregation*: for example, where multiple component carriers of 20 MHz are aggregated to support transmission bandwidths of up to 100 MHz; MHz are aggregated to form a larger overall bandwidth of up to 100 MHz to provide for very high data rates.
- *Relaying* to improve coverage and reduce deployment cost.
- *Extended multi-antenna transmission*, increasing the number of downlink transmission layers to eight and the number of uplink transmission layers to four, to increase the data rates.
- *Coordinated multipoint (CoMP) transmission/reception*, where transmission/reception is performed jointly across multiple cell sites (mainly) to improve cell-edge performance. To some extent, CoMP can be seen as an extension of ICIC, already present in the first release of the specifications.

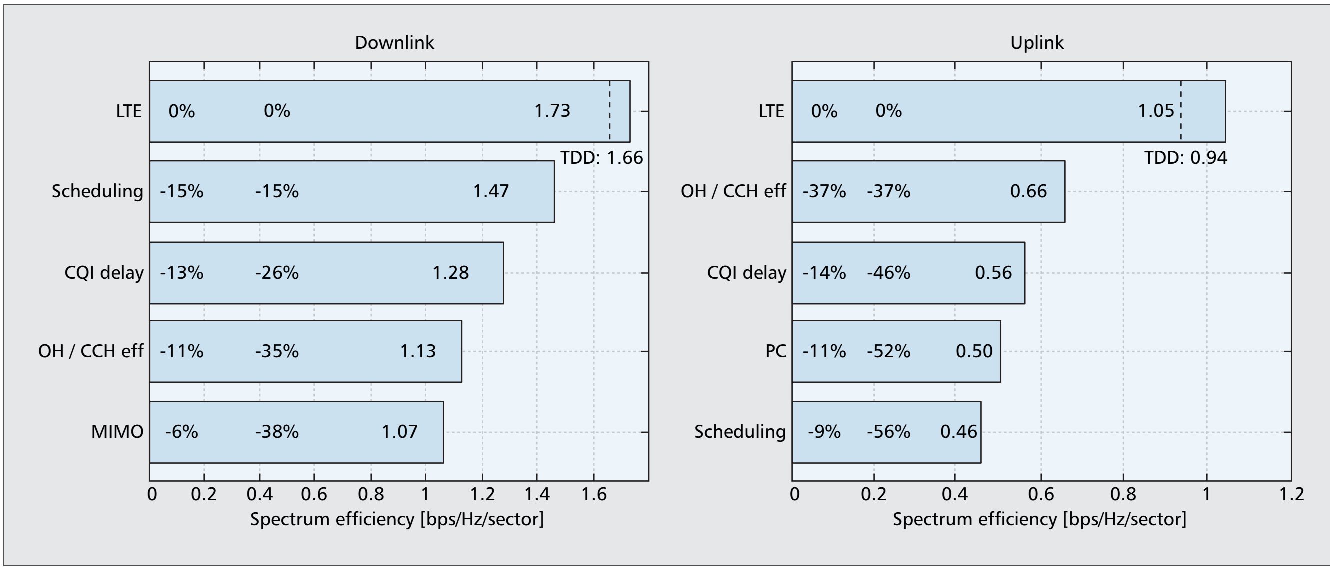


Figure 6. *Spectrum efficiency in downlink and uplink.*

It is important to note that LTE-Advanced is an *evolution* of LTE and not a new system. LTE-Advanced terminals will be able to access networks built according to the first release of the LTE specifications; as well, terminals from the first LTE release will be able to access LTE-Advanced networks. This is essential to provide a smooth introduction of new features in a cost-efficient way where and when the need arises.

CONCLUSION

This article provides a high-level overview of LTE and some of its key components: spectrum flexibility, multi-antenna transmission, and ICIC. Numerical simulations are used to show the performance of the first release of LTE, as well as assess the benefit of the key features. Indeed these contribute strongly to LTE meeting its performance targets. An outlook of the evolution of LTE toward LTE-Advanced and full IMT-Advanced capabilities complete the article. Clearly, LTE offers highly competitive performance and provides a good foundation for further evolution.

REFERENCES

[1] E. Dahlman *et al.*, *3G Evolution: HSPA and LTE for Mobile Broadband*, 2nd ed., Academic Press, 2008.
[2] 3GPP TS36.300, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN): Overall Description."
[3] D. Astély *et al.*, "A Future Radio-Access Framework," *IEEE JSAC*, vol. 24, no. 3, Mar. 2006.
[4] A. Larmo *et al.*, " The LTE Link Layer Design," *IEEE Commun. Mag.*, Apr. 2009.
[5] 3GPP TR 25.913, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)," v. 7.0.0.
[6] NGMN, "NGMN Radio Access Performance Evaluation Methodology," v. 1.2, June 2007; www.ngmn.org
[7] NGMN, "Next Generation Mobile Networks Beyond HSPA and EVDO," v. 1.3, Dec. 2006; www.ngmn.org
[8] 3GPP TR 36.913, "Requirements for Further Advancements for E-UTRA."
[9] ITU-R Rec. M.1645

BIOGRAPHIES

DAVID ASTÉLY received a Ph.D. degree in electrical engineering from the Royal Institute of Technology, Stockholm, Sweden in 1999. He has been with Ericsson since 2001, where he is currently with Ericsson Research as a technical coordinator working in the research and standardization of future cellular technologies, primarily within the areas of advanced antenna systems and time division duplex. From 1999 to 2001, he was with Nokia Networks.

ERIK DAHLMAN is currently the senior expert in radio access technologies within Ericsson Research. Most recently, he has been involved in the standardization and development of the 3GPP long term evolution (LTE) and its evolution towards LTE-Advanced. He also was deeply involved in the development and standardization of 3G radio access technologies, first in Japan, and later within the global 3GPP standardization body. He is the co-author of the book *3G Evolution – HSPA and LTE for Mobile Broadband*.

ANDERS FURUSKÄR received his M.S. degree in electrical engineering and his Ph.D. degree in radio communications systems from the Royal Institute of Technology in 1996 and 2003, respectively. Currently, he holds a position as an expert with focus on radio resource management and performance evaluations of wireless networks at Ericsson. He joined Ericsson Research in 1997, working mainly in the standardization of third-generation cellular systems.

YLVA JADING received her Master's of Engineering from Chalmers University of Technology, Gothenburg, in 1992 and a Ph.D. in nuclear astrophysics from Johannes Gutenberg Universität, Mainz, in 1996. Currently, she is a senior researcher and is involved in concept and standardization work for LTE and LTE-Advanced, both within Ericsson Research and in the standardization body, 3GPP. She joined Ericsson 1999, driving system characteristics verification for TDMA and WCDMA standards. From 1996 to 1999 she worked at CERN, Geneva.

MAGNUS LINDSTRÖM received his M.S. degree in electrical engineering from the Royal Institute of Technology, Stockholm, in 1997. He received his Ph.D. degree in radio communication systems from the Royal Institute of Technology in 2005. He has been with Ericsson Research since 2005, working in research on radio resource management and radio protocols. He is active in concept development and 3GPP standardization of LTE and future wireless technologies.

STEFAN PARKVALL [SM] (stefan.parkvall@ericsson.com) is currently a senior specialist in adaptive radio access at Ericsson Research, is actively participating in 3GPP physical-layer standardization, and is heavily involved in the development of HSPA, LTE, and LTE-Advanced. He is co-author of the popular book, *3G Evolution — HSPA and LTE for Mobile Broadband*. His previous positions included Assistant Professor in communication theory at the Royal Institute of Technology, Stockholm, Sweden, and Visiting Researcher at the University of California, San Diego.