The Evolution of LTE towards IMT-Advanced

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Abstract— **This paper provides a high-level overview of some technology components currently considered for the evolution of LTE, referred to as LTE-Advanced. First, a brief overview of LTE and some of its technologies are given and then the IMT-Advanced requirements are discussed. One of the targets with the evolution of LTE is to reach or seven surpass these requirements. The technology components considered for LTE-Advanced include extended spectrum flexibility to support up to 100MHz bandwidth, enhanced multi-antenna solutions with up to eight layer transmission in the downlink and up to four layer transmission in the uplink, coordinated multi-point transmission/reception, and the use of advanced repeaters/relaying.**

Index Terms— **LTE, IMT-Advanced, LTE-Advanced, 4G**

I. INTRODUCTION

The LTE as defined by 3GPP is a highly flexible radio interface [1][2] with initial deployments expected in 2009. The first release of LTE, referred to as release-8 provides peak rates of 300 Mbit/s, a radio-network delay of less than 5 ms, a significant increase in spectrum efficiency and a new flat radio-network architecture designed to simplify operation and to reduce cost. LTE supports both FDD and TDD and targets also a smooth evolution from earlier 3GPP system such as TD-SCDMA and WCDMA/HSPA as well as 3GPP2 systems such as cdma2000.

LTE also constitutes a major step towards IMT-Advanced as will be discussed below. In fact, already the first release of LTE includes many of the features originally considered for future fourth generation systems.

As the work on this first release of the LTE standard is coming to an end, the focus in 3GPP is now gradually shifting towards the further evolution of LTE, referred to as LTE-Advanced. One of the goals of this evolution is to reach and even surpass the requirements on IMT-Advanced, as currently being defined by ITU-R [3]. These requirements will include further significant enhancements in terms of performance and capability compared to current cellular systems, including the first release of LTE.

In this paper, an overview of the first release of LTE, release-8, is provided. The basic transmission schemes in uplink and downlink are described, and one of the key features of LTE, spectrum flexibility, is outlined. Other technology components such as multiple antenna transmission as well as inter-cell interference coordination are also addressed. This is followed by an introduction of the requirements on the evolution of LTE, including the IMT-Advanced requirements. Finally, some potential key technology components to fulfill these requirements, such as carrier aggregation, enhanced multi-antenna transmission, coordinated multi-point transmission and the use of advanced repeaters/relaying, are discussed.

II. LTE – AN OVERVIEW

To set the background for LTE-Advanced, it is necessary to briefly describe the existing LTE system, known as LTE Rel-8.In the following, a brief overview of the first release of LTE is given.

A. Basic Transmission Scheme

Orthogonal frequency-division multiplexing (OFDM), with data being 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 narrow-band subcarriers in combination with a cyclic prefix, OFDM transmission is inherently robust to time dispersion on the radio channel without having to resort to advanced and often relatively complex receiver-side channel equalization. For the downlink, this is an attractive property as it simplifies the receiver baseband processing with a reduced terminal cost and power consumption as consequences. This is especially important taking into account the wide transmission bandwidths of LTE and even more so in combination with advanced downlink multi-antenna transmission such as spatial multiplexing.

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 signal processing in the receiver, one of the most important factors in the uplink design is to allow for highly power-efficient transmission. This will improve coverage and reduce terminal cost and power consumption at the transmitter. For this reason, single-carrier transmission based on DFT-precoded OFDM, sometimes referred to as Single-Carrier FDMA, is used for the LTE uplink. DFT-precoded OFDM has smaller peak-to-average-power-ratio than regular OFDM, thus enabling less-complex and/or higher-power terminals.

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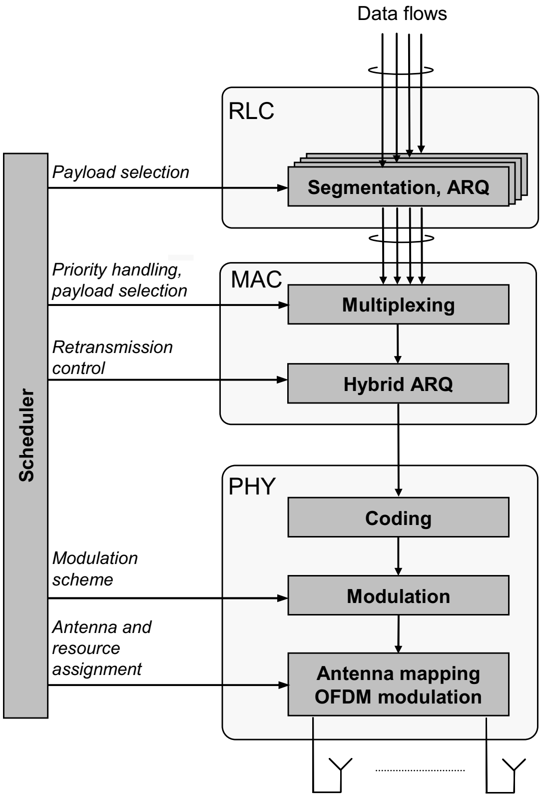


Figure 1. LTE protocol structure (simplified)

The basic protocol structure of LTE is illustrated in Figure 1. The RLC and MAC layers are, among other things, responsible for retransmission handling as discussed further below. In the physical layer, data to be transmitted is turbo coded and modulated using one of QPSK, 16QAM or 64QAM, followed by OFDM modulation. The subcarrier spacing is 15 kHz and one of 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 cyclic prefix of 16.7 μs for highly-dispersive environments. In the downlink, different types of multi-antenna processing, further described below, is applied prior to OFDM modulation. 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 with ten subframes forming a radio frame. The short subframe duration of 1 ms results in small delays, not only for user data, but also for control signaling such as the channel-quality feedback from the terminals to the base station facilitating channel-dependent scheduling.

LTE can operate in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) as illustrated in Figure 2. Although the time-domain structure is, in most respects, the same for FDD and TDD there are some differences between the two duplex modes, most notably the presence of a special subframe in case of TDD. The special subframe is used to provide the necessary guard time for downlink-to-uplink switching as discussed below.

In case of FDD operation (upper part of Figure 2), there are two carrier frequencies, one for uplink transmission (f_{UL}) and one for downlink transmission (f_{DL}). During each frame, there are thus ten uplink subframes and ten downlink subframes and uplink and downlink transmission can occur simultaneously within a cell.

In case of TDD operation (lower part of Figure 2), there is only a single carrier frequency and uplink and downlink transmissions are always separated in time also on a cell basis. The guard period necessary to support TDD operation is created by splitting one or two of the ten subframes in each radio frame into three special fields, a downlink part (DwPTS), a guard period, and an uplink part (UpPTS). The lengths of the special fields are configurable to allow for different deployment scenarios. This does not only allow to support variable cell ranges up to 100km, but more importantly allows for efficient coexistence with TD-SCDMA since the length of uplink and downlink periods can be chosen to avoid interference between uplink and downlink of adjacent carriers. This in turn allows for a smooth migration from TD-SCDMA to LTE since uplink and downlink periods can be aligned. Whereas the downlink field, DwPTS is to be used for data transmission like any other downlink subframe, the main difference being the somewhat shorter duration, the uplink part (UpPTS) can be used for uplink channel sounding targeting for example exploitation of channel reciprocity.

Virtually all the baseband processing is identical for FDD and TDD, allowing for low-cost implementation of terminals supporting both FDD and TDD mode of operation. One difference between FDD and TDD stem from the fact that uplink and downlink are not continuous which in turn calls for slightly different uplink-downlink timing relations for control signaling such as hybrid ARQ feedback.

Channel-dependent scheduling and link adaptation are well-known tools for exploiting channel variations and are applied in several cellular systems, e.g. HSPA. 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 rapid channel-quality variations, thereby achieving more efficient utilization of the available radio resources. The scheduler determines, for each 1 ms subframe, which users(s) that are allowed to transmit, on what frequency resources transmission is to take place, and what data rate to use. This allows for also relatively fast channel variations to be tracked and utilized by the scheduler. In the frequency domain, the scheduling granularity is 180 kHz. The scheduler is thus a key element and to a large extent determines the overall 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 from the

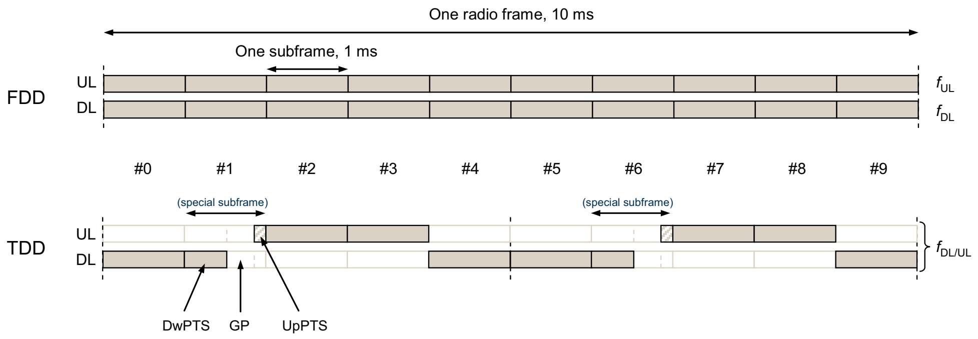


Figure 2. LTE frame structure.

cell-specific reference signals 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 quality of which may be used for uplink channel dependent scheduling and link adaptation. In case of TDD operation, channel reciprocity may also be exploited, an example being using uplink measurements for adapting downlink transmissions. To handle situations where channel-dependent scheduling is not possible or desirable, LTE also supports means for achieving frequency-domain diversity.

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. The use of a two-layered mechanism achieves low latency and overhead without sacrificing reliability. Most errors are captured and corrected by the light-weight hybrid ARQ protocol, which provides feedback to the transmitter after each transmitted subframe, and only rarely the, in terms of latency and overhead, more expensive ARQ retransmissions are needed. The tight coupling between the two retransmission layers is possible as both mechanisms are terminated in the base station.

To support the LTE features, scheduling decisions, hybrid-ARQ feedback, channel-status reports and other control information need to be communicated between the base station and the terminal. In the downlink, the control signaling is transmitted using up to three of the first OFDM symbols in a 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 and uplink used for control signaling can be varied dynamically to minimize the overhead.

B. *Spectrum Flexibility*

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

LTE is not only able to operate in different frequency bands but can also be deployed with different bandwidths in order to be able to operate in spectrum of different size as well as allow for efficient migration of other radio-access technologies to LTE. More specifically, LTE allows for an overall system bandwidth ranging from as small as 1.4 MHz up to 20 MHz, where the latter is needed to provide the highest LTE data rates. All terminals will support the widest bandwidth.

A unique LTE possibility is the possibility to use different uplink and downlink bandwidths, allowing for asymmetric spectrum utilization. Furthermore, as already mentioned, LTE enables operation in both paired and unpaired spectrum by supporting both Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) operation with a single radio-access technology.

From a terminal point-of-view, FDD allows for operation in full-duplex as well as in half-duplex. Half-duplex FDD, in which the terminal separates transmission and reception not only in frequency but also in time, is useful as it allows terminal operation without a duplex filter, thereby reducing terminal cost and providing support for FDD frequency bands otherwise not possible to exploit due to narrow duplex distance.

To allow 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. Once the terminal has acquired the system information, the cell bandwidth and the duplexing scheme is known and the terminal can access the cell based on this knowledge.

C. *Multi-Antenna Transmission*

Support for multi-antenna transmission is an integral part of LTE from the first release and the channel quality measurements for link adaptation and scheduling are designed to cater for this. The fact that all terminals support at least two receive antennas is important, as it allows the networks to be planned assuming at least the presence of downlink receive diversity. More advanced multi-antenna schemes are also supported by LTE, including transmit diversity, spatial multiplexing (including both so-called single-user MIMO as well as multi-user MIMO), and beam-forming. Which of the scheme (or which combination of schemes) to use depends on the scenario. 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 Shift Transmit Diversity (FSTD) in case of four transmit antennas. 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 can also be applied to user-data transmission, e.g. 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, up to four 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 quadrupling the data rate.

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 carried out and reported by the terminal. This is also known as closed-loop spatial multiplexing.

In case of spatial multiplexing, by selecting rank-1 transmission, the precoder matrix performs a (single-layer) beam-forming function. This type of beam-forming is referred to as codebook-based beam-forming as the beam-forming can only be done according to a limited set of pre-defined beam-forming (precoder) vectors.

In addition to the codebook-based beam-forming as a special case of the LTE spatial multiplexing, LTE also supports more general non-codebook-based beam-forming. In this case, the transmitting base station is not constrained to select precoder vectors from a certain limited set of precoders, but can exploit channel reciprocity to adjust the downlink transmission weights from channel estimates obtained from uplink transmissions such as sounding reference signals. For the case with FDD operation, longer-term direction of arrival based beam-forming is one candidate, whereas for TDD also short-term precoding based on instantaneous channel knowledge is possible.

In contrast to codebook-based beam-forming, in case of non-codebook-based beam-forming the terminal needs to make an estimate of the overall beam-formed channel. To enable this, LTE provides the possibility for the transmission of UE-specific reference symbols, being transmitted using the same beam-forming as the user data, and allowing for the terminal to estimate the overall beam-formed channel. Another aspect of this is that the number of transmit antennas used for the non-codebook based precoding is not constrained by the number of available cell-specific reference signals.

D. Inter-Cell Interference Coordination

LTE provides orthogonality between users within a cell in both uplink and downlink, i.e. at least in principle there is no interference between transmissions within one cell (no intra-cell interference). 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. Means to reduce or control the inter-cell interference can therefore, potentially, 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 not only to control the received signal strength in the intended cell, but also to control the amount of interference in neighboring cells.

Inter-cell interference coordination is a scheduling strategy, used to control the inter-cell interference in both uplink and downlink. A simple method to improve cell-edge data rates is to statically restrict the usage of parts of the bandwidth, e.g., through a reuse larger than one. Such schemes improve the signal-to-interference ratios of the used frequencies. However, the loss due to a reduced bandwidth availability is typically larger than the corresponding gain due to higher signal-to-interference ratio, leading to an overall loss of efficiency. The LTE standard therefore provides tools for inter-cell interference coordination of the scheduling in neighbor cells such that cell-edge users in different cells are preferably scheduled on complementary parts of the spectrum when needed. 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 only applied when traffic and radio conditions motivate this.

To aid uplink inter-cell coordination, LTE defines two indicators that can be exchanged between base stations: the high-interference indicator, providing information to neighboring cells about the part of the cell bandwidth upon which the cell intends to schedule its cell-edge users, and the overload indicator, used to indicate the experienced interference level in each part of the bandwidth to neighboring cells. The rate with which these indicators can be exchanged between cells is implementation-dependent, but typically rates are in the order of a couple of times per second.

II. LTE-ADVANCED – REQUIREMENTS

With the first release of LTE, release-8, as background, the evolution of LTE towards IMT-Advanced can be discussed. IMT-Advanced is the term used by ITU for radio-access technologies beyond IMT-2000 and an invitation to submit candidate technologies for IMT-Advanced has been issued by ITU [5]. Along with the invitation, ITU has also defined a set of requirements to be fulfilled by any IMT-Advanced candidate technology. Some of the key requirements are summarized in Table I with the full set of requirements and associated assumptions listed in [4].

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 the technology components for the evolution of LTE to fulfill all the requirements of IMT-Advanced as defined by ITU.

Although the term LTE-Advanced is used frequently, it is important to stress that this is not a new radio-access scheme but rather the *evolution* of LTE to further improve the performance. LTE-Advanced is thus a name for a future release of the LTE standard, currently predicted to release-10. Being an evolution of LTE, LTE-Advanced should be backwards compatible in the sense that it should be possible to deploy LTE-Advanced in spectrum already occupied by the first release of LTE with no impact on existing LTE terminals. A direct consequence of this requirement is that, for an LTE terminal, an LTE-Advanced-capable network should appear as an LTE network. Such spectrum compatibility is of critical importance for a smooth, low-cost transition to LTE-Advanced capabilities within the network and is similar to the evolution of WCDMA to HSPA.

In addition to the fundamental requirement of being an *evolution* of LTE and thus backwards compatible, the 3GPP has defined a set of targets [5] to be fulfilled by LTE-Advanced. These requirements are a *superset* of the IMT-Advanced requirements, i.e., LTE-Advanced will fulfill, and sometimes even surpass, the IMT-Advanced requirements. For example, the spectrum efficiency requirements are significantly higher for LTE-Advanced than for IMT-Advanced as illustrated in Table I. In fact, many of the IMT-Advanced requirements are close to be fulfilled already with the first release of LTE.

As can be seen in Table I, requirements are set not only on the peak spectral efficiency, but also on the average and cell-edge spectral efficiency. The latter are, in most practical deployments, more important than the peak rates and [5] therefore explicitly states that “special focus should be put on improving the cell edge performance” to provide a reasonably homogenous user experience across the cell.

LTE-Advanced will also provide further enhanced spectrum flexibility beyond the capabilities of LTE Rel-8 and be capable of exploiting spectrum allocations up to 100 MHz.

To fulfill these requirements, 3GPP is currently studying several key components, the main one which are described in more detail in the following section.

TABLE I. ITU AND 3GPP REQUIREMENTS.

Quantity		IMT-Advanced	LTE-Advanced
Peak data rate	UL		1 Gbit/s
	DL		500 Mbit/s
Spectrum allocation		Up to 40 MHz	Up to 100 MHz
Latency	User plane	10 ms	10 ms
	Control plane	100 ms	50 ms
Spectrum efficiency (4 ant BS, 2 ant terminal)	Peak	15 bit/s/Hz DL 6.75 bit/s/Hz UL	30 bit/s/Hz DL 15 bit/s/Hz UL
	Average	2.2 bit/s/Hz DL 1.4 bit/s/Hz UL	2.6 bit/s/Hz DL 2.0 bit/s/Hz UL
	Cell-edge	0.06 bit/s/Hz DL 0.03 bit/s/Hz UL	0.09 bit/s/Hz DL 0.07 bit/s/Hz UL

II. LTE-ADVANCED – TECHNOLOGY COMPONENTS

The link performance of current cellular systems such as LTE is already quite close to the Shannon limit. From a pure link-budget perspective, the very high data rates targeted by LTE-Advanced require a higher SNR than what is typically experienced in wide-area cellular networks. Although some link improvements are possible, e.g. using additional bandwidth as a means to improve the coding/modulation efficiency, it is necessary to find tools for improving the signal-to-noise ratio. Especially improvements at the cell edge are of interest as a means to enhance the user experience.

In the following subsections, some examples of technologies considered for LTE-Advanced are outlined. It is worth noting that LTE-Advanced is currently under discussion in 3GPP and which technology components to include and the final details are still open.

A. Carrier Aggregation

As discussed in Section II, already the first release of LTE provides extensive support for deployment in spectrum allocations of various characteristics, ranging from around 1.4 MHz up to 20 MHz in both paired and unpaired bands. The very high peak-data rate targets for LTE-Advanced can only be fulfilled in a reasonable way with a further increase of the transmission bandwidth, compared to what is supported with the first release of LTE. Henceforth, LTE-Advanced can exploit spectrum allocations up to 100 MHz. At the same time, such a bandwidth extension should be done while preserving spectrum compatibility as discussed in Section II. In LTE-Advanced, this is achieved with so-called *carrier aggregation*, where multiple component carriers are aggregated to provide the necessary bandwidth. Carrier aggregation is illustrated in Figure 3. To an LTE Rel-8 terminal, each component carrier will appear as an LTE carrier, while an LTE-Advanced terminal can exploit the total aggregated bandwidth.

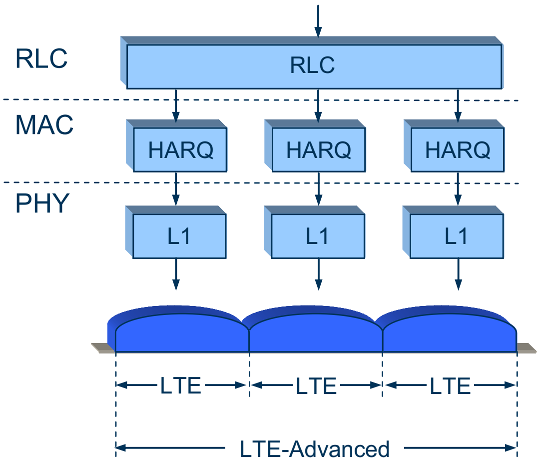


Figure 3. Example of carrier aggregation.

Access to large amounts of contiguous spectrum, in the order of 100 MHz, may not always be possible. The use of carrier aggregation provides a tool for alleviating this. From a baseband perspective, there is no difference if the component carriers are contiguous in frequency or not. This could allow for aggregating non-contiguous spectrum fragments by allocating different fragments to different component carriers. However, it should be noted that aggregation of non-contiguous spectrum is challenging from an implementation perspective. Thus, although spectrum aggregation would be 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.

For a component carrier to be accessible by an LTE release-8 terminal, synchronization signals and broadcast channels need to be present. On the other hand, for an LTE-Advanced terminal capable of receiving multiple component carriers, it can be sufficient if these signals are available on one of the component carriers only. Hence, an operator can, by enabling/disabling these signals, control which part of the spectrum that should be accessible to LTE terminals. From this it also follows, that certain non-backwards compatible elements can be considered given that significant benefits or gains can be achievable. Whether carrier aggregation is used or not, and which component carriers to aggregate, is provided to the LTE-Advanced terminals as part of the system information.

Aggregation of the component carriers can in principle be done at different layers in the protocol stack, In LTE-Advanced, the data streams from the different component carriers are aggregated above the MAC layer as shown in Figure 3. This implies that hybrid-ARQ retransmissions are performed independently per component carrier. In principle, transmission parameters such as modulation scheme and code rate could also be selected per component carrier. Having a structure allowing for independent operation per component carrier is especially useful in case of aggregating component carriers from different frequency bands with different radio-channel quality. The fact that the physical layer processing of each component carrier is identical to Rel-8 is also highly beneficial from an implementation and specification perspective. Existing implementations can, to a large extent, be reused, thereby shortening the time-to-market for LTE-Advanced equipment.

B. Enhanced Multi-antenna transmission

In addition to wider bandwidth, LTE-Advanced is also expected to provide higher data rates and improved system performance by further extending the support for multi-antenna transmission compared to the first release of LTE. For the downlink, up to eight layers can be transmitted using an 8×8 antenna configuration, allowing for a peak spectral efficiency exceeding the requirement of 30 bit/s/Hz and implying a possibility for data rates beyond 1 Gbit/s in a 40 MHz bandwidth and even higher data rates with wider bandwidth. This calls for the introduction of additional reference signals not only for channel estimation but also for measurements such as channel quality to enable adaptive multi-antenna transmission. Backwards compatibility needs to be considered and both additional cell-specific as well as additional UE-specific reference signals are possible candidates.

Furthermore, LTE-Advanced will include spatial multiplexing of up to four layers also for the uplink. With four-layer transmission in the uplink, a peak uplink spectral efficiency exceeding 15 bit/s/Hz can be achieved. Many of the techniques employed for downlink spatial multiplexing already in LTE Rel-8 such as codebook-based and non-codebook-based channel-dependent precoding can be considered in order to not only enhance peak rates but also cell-edge data rates.

C. Coordinated Multi-point Transmission

Coordinated Multi-Point transmission and reception (CoMP) is another technique being extensively discussed within the context of LTE-Advanced. The basic idea behind CoMP is to apply tight coordination between the transmissions at different cell sites, thereby achieving higher system capacity and, especially important, improved cell-edge data rates. Coordination schemes can be divided into two categories, used either alone or in combination:

- dynamic scheduling coordination between multiple cells
- joint transmission/reception from multiple cells

In the former case, CoMP can to some extent be seen as an extension of the inter-cell interference coordination part present already in LTE Rel-8. In LTE-Advanced, the coordination can be in terms of the scheduling at the different cell sites, thereby achieving an even more dynamic and adaptive inter-cell interference coordination. Alternatively, or as a complement, transmissions can be carried out to a mobile terminal jointly from several cell sites, thereby not only reducing the interference but also increasing the received power. The transmission from the cell sites can also take the instantaneous channel conditions into account, thereby achieving multi-cell beam-forming or precoding gains.

The channel-estimate required for demodulation of the downlink transmission at the terminal can basically be obtained using either cell-specific or UE-specific reference signals, as illustrated in Figure 4.

If cell-specific reference signals are used, the terminal need to know the transmission weights applied at the different transmission points. In essence, this implies defining a set of standardized transmission weights, a codebook, to be used for CoMP. Different deployment scenarios in terms of antenna placement, cell sizes, propagation conditions, etc may require different codebooks, which may complicate the overall design. Thus, in this approach, the terminal need to know the transmission weights used by all transmission points from which it is supposed to receive the downlink transmission.

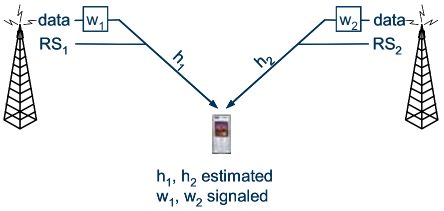
Alternatively, UE-specific reference signals can be applied as shown at the bottom of Figure 4. In this case, the reference signal is subject to the same transmitter-side precoding as the data prior to transmission from the multiple transmission points. There is no need for the terminal to know which set of transmission points that are involved in the transmission. Downlink CoMP is in this case *invisible* to the terminal and can, in principle, be applied also to Rel-8 terminals. As there is no need to standardize the codebook, different deployments can be handled as part of the network implementation.

To determine the CoMP processing to apply on the transmitter side, channel knowledge is needed by the network. This can be accomplished by generalizing the single-cell channel-status reports in LTE to multi-cell reports, i.e., the terminal need to report the perceived channel-quality from *multiple* cells. Estimating the channel quality can be done by exploiting the cell-specific reference signals already transmitted.

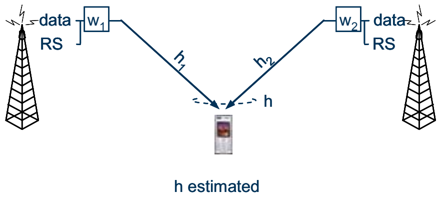
In the uplink, the receiver processing is implementation specific and no major specification impact is foreseen. Consequently, it can be applied also to Rel-8 terminals. In principle, uplink CoMP is similar to softer handover applied already in WCDMA networks. Maximum-ratio combining and interference-rejection combining are examples of schemes that can be used to combine the uplink transmission received at multiple points.

D. Relaying

The very high data rates targeted by LTE-Advanced requires, as already mentioned, a tighter infrastructure. Coordinated multipoint transmission, described above, is one possibility for deploying a denser infrastructure. Another possibility for providing a denser infrastructure from a link-budget perspective is to deploy different types of relaying solutions. In essence, the intention is to reduce the transmitter-to-receiver distance, thereby allowing for higher data rates.



Demodulation based on cell-specific RS



Demodulation based on UE-specific RS

Figure 4. Downlink CoMP transmission.

Depending on the scheme applied, different types of relaying solutions can be envisioned, although they all share the basic property of relaying the communication between the *donor* cell and the terminal. The donor cell may, in addition to serving one or several relays, also communicate directly with other terminals.

The simplest form of relay is a repeater, which simply *amplify and forward* the received analog signals. Repeaters and are used already today, e.g. for handling coverage holes. Traditionally, once installed, repeaters continuously forwards the received signal regardless of whether there is a terminal in its coverage area or not. Such repeaters are invisible to both the terminal and the base station. More advanced repeater structures can also be considered, e.g. schemes where the network can control the transmission power of the repeater and, for example, activate the repeater only when users are present in the area handled by the repeater in order to increase the supported data rates in the area. Irrespective of these mechanisms, as they simply amplify-and-forward the received signal, repeaters are backwards compatible in the sense that they are invisible to the terminal and hence also can serve Rel-8 terminals. All radio-resource management functions such as mobility, scheduling, retransmission mechanism are handled by the base station.

The intermediate relay node may also decode and re-encode any received data prior to forwarding it to the served users. This is often referred to as *decode-and-forward* relaying. As the intermediate node decodes and re-encodes received data blocks a significant delay is introduced, longer than the LTE subframe duration of 1 ms. However, no noise or interference is forwarded by the relay node and rate adaptation may be performed individually for each link. As for repeaters, many different options exist depending on supported features (e.g. support of more than two hops, support of mesh structures). Although very similar in their basic characteristics (e.g. introduction of delays and avoidance of noise amplification), different relaying structures have different properties depending on which functions that are controlled by the relay.

A straightforward relaying solution is to let the relay perform the same functions as normally handled by the base station, e.g. hybrid-ARQ retransmissions, scheduling, and mobility functions. In essence, the relay is, from a functional perspective, a base station and therefore there is no need to define *new* functions for mobility. This relaying solution is sometimes referred to as *self-backhauling* or "layer-3" relaying. Since the relay from a logical perspective is identical to a base station, it will be capable of handling Rel-8 terminals, which is highly beneficial from a backwards compatibility perspective. Naturally, although the relay acts as a base station from a functional perspective, its physical implementation may still be different, e.g. lower output power and smaller size than a regular base station.

Another possibility is to only keep part of the radio-resource control in the relay, e.g. hybrid-ARQ retransmissions and scheduling, while keeping other functions, e.g. mobility handling, in the base station. Such relaying schemes, sometimes referred to as "layer-2" relaying, may require new mobility mechanisms to be defined, e.g. relay-to-base-station handover, in which case they will *not* be backwards compatible with Rel-8. It is also questionable if there are any gains with this type of relaying compared to self backhauling.

Regardless of the decode-and-forward relaying solution, there is a need for anchor-to-relay communication, preferably operating in the same spectrum as communication to/from the terminals. Simultaneous reception from the donor cell and transmission to terminals by the relay can be troublesome due to interference from the relay downlink transmitter to the relay downlink receiver. Similarly when the relay is transmitting in the uplink to the donor cell, it may be troublesome to receive uplink transmissions from terminals.

Hence, it is necessary to operate the relay such that the relay is not transmitting in the downlink when it is supposed to receive data from the donor cell, i.e. to create gaps in the relay-to-terminal transmission. Note that, if the relay is to serve Rel-8 terminals as well, the mechanisms to create the gaps must be present already in Rel-8. Otherwise, the terminals would expect downlink transmission, at least in the form of cell-specific reference signals, in each (downlink) subframe. Such a mechanism is actually included already in the first release of LTE in the form of MBSFN (multicast-broadcast single-frequency network) subframes, originally introduced for single-frequency broadcasting transmissions. In an MBSFN subframe, the terminal will not expect downlink transmission (except for the first OFDM symbol(s)). Consequently, the remaining part of the MBSFN subframe can be used for donor-to-relay communication as illustrated in Figure 5.

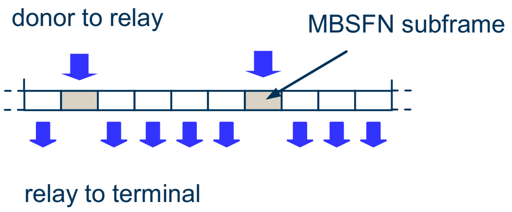


Figure 5. Backhaul transmission using MBSFN subframes.

IV. CONCLUSION

The highly flexible LTE radio interface has been described. Already its first release, Release 8, supports very high data rates, up to 300 Mbit/s, and is capable of fulfilling many of the IMT-Advanced performance targets. The evolution of LTE, often referred to as LTE-Advanced, will incorporate additional technology components to further enhance the performance beyond the IMT-Advanced requirements while maintaining backwards compatibility with earlier releases of LTE. The technology components being considered for LTE-Advanced include carrier aggregation, both for contiguous and non-contiguous spectrum to support bandwidths up to 100MHz as well as enhanced multiple antenna transmission with up to eight layers in the downlink and up to four layers in the uplink. In addition to relaying and repeater solutions to enhance coverage and cell edge data rates, an evolution of the inter-cell interference coordination in the form of coordinated multipoint transmission/reception is yet another technology to enhance performance.

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