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3G Radio Access Evolution — HSPA and LTE for Mobile Broadband —

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SUMMARY This paper provides an overview of the 3GPP radio-access technologies for mobile broadband — HSPA and its evolution, and LTE. The paper also discusses the current stage of the 3GPP activities on evolving LTE towards LTE-Advanced and full IMT-Advanced compliance.

key words: *3G evolution, HSPA, LTE, IMT-Advanced, LTE-Advanced, 4G*

1. Introduction

Roughly eight years have passed since the first commercial deployment of 3G mobile communication based on the WCDMA radio-access technology developed by 3GPP*. Since then, the 3GPP radio-access technologies have gone through several steps of evolution and improvements, further boosting their capabilities in terms of the services that can be provided as well as the basic system performance.

In parallel to the direct evolution of WCDMA into HSPA and its continuing evolution, there has also in 3GPP been a development of a new radio-access technology, the *Long Term Evolution* (LTE). LTE is now further evolving, an evolution often referred to as *LTE-Advanced* and aiming, among other things, at full compliance with all the capabilities and expectations for so-called IMT-Advanced radio access [5].

This paper provides an overview of the 3GPP radio-access technologies for broadband mobile communication including HSPA and its evolution, and LTE. The paper also discusses the current stage of the 3GPP activities on evolving LTE towards LTE-Advanced.

For more detailed information about HSPA and its evolution as well as LTE, the reader is referred to [1]. The full specifications for HSPA and LTE can be found at www.3gpp.org (the 25.xxx and 36.xxx series of specifications respectively).

2. HSPA — The First Step of 3G Evolution

The first step in the evolution of 3G radio access was taken by extending WCDMA with *High Speed Downlink Packet Access* (HSDPA). Introduced as part of 3GPP release 5 in 2002, HSDPA extended WCDMA with several new features to enhance the support for downlink packet access in terms of improved service quality and enhanced system performance, including

- Support for *higher-order modulation* (16QAM).
- Use of *shared-channel transmission* where a set of channelization codes is a common resource dynamically shared between users.
- Possibility for *fast channel-dependent scheduling* and *link adaptation* dynamically selecting the user to transmit to, as well as the data rate to use for the transmission, based on the instantaneous channel conditions.
- Use of *fast hybrid-ARQ* (HARQ) with *soft combining* to rapidly correct transmission errors occurring on the radio link.

In order for a terminal to know if there is data transmission within a given subframe and, if so, on what set of channelization codes and with what transport format (modulation scheme and coding rate) the data transmission is carried out, the terminal continuously monitors a set of downlink control channels, the so-called *High-Speed Control Channels* (HS-SCCH), that carry this information. There is also HSDPA-related *uplink* control signaling to convey the hybrid-ARQ feedback and to provide the base station with knowledge about the instantaneous channel conditions needed for downlink channel-dependent scheduling and link adaptation.

The introduction of HSDPA was followed by the introduction of *Enhanced Uplink*, sometime also referred to as *High Speed Uplink Packet Access* (HSUPA), in WCDMA release 6 finalized in 2005. Aimed at boosting the support for uplink packet access, Enhanced Uplink extends WCDMA with *fast uplink scheduling* and *fast uplink hybrid-ARQ*.

WCDMA extended with HSDPA and Enhanced Uplink is often referred to as *HSPA* (*High Speed Packet Access*). HSPA is today a well-established technology introduced in close to 220 commercial networks in more than 100 countries and with currently more than 75 million subscribers. The introduction of HSPA has significantly improved system performance, such as improved system capacity, as well as enhanced the service provisioning including the possibility for data rates up to 14 Mbps in the downlink and 5.6 Mbps in the uplink, as well as a reduced latency.

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*3GPP = Third Generation Partnership Project.

3. HSPA Evolution

Although HSPA in itself provides substantial benefits compared to the first release of WCDMA, there is a continued desire for further improved system performance and network capabilities in order to satisfy the always increasing traffic and end-user demands. Thus, there has been, and still is, a corresponding continued evolution of HSPA, some steps of which will here be described.

3.1 Extended Use of Higher-Order Modulation

HSDPA introduced downlink higher-order modulation, more exactly 16QAM modulation, providing the possibility for downlink peak data rates up to 14 Mbps. As part of the evolution of HSPA, support for 64QAM modulation has later also been introduced, raising the maximum downlink data rate to roughly 21 Mbps. In addition, 16QAM modulation has been introduced for the uplink transmission direction, raising the maximum uplink data rate to more than 11 Mbps.

3.2 Spatial Multiplexing

Already the first release of WCDMA included support for downlink *multi-antenna* transmission in form of *open-loop* and *closed-loop transmit diversity*. These diversity schemes are also supported for HSPA. However, as part of the evolution of HSPA, the possibility for downlink *spatial multiplexing,* often referred to as MIMO (*Multi-Input-Multi-Output*) antenna processing, has also been introduced. Spatial multiplexing relies on the use of multiple antennas at both the transmitter and the receiver side to enable the transmission of *multiple parallel streams*, also referred to as *layers*, over the same radio link within the same frequency band. The support for spatial multiplexing offers the possibility for a substantial increase in the data rates that can be provided over a radio link, especially in case of good channel conditions.

For HSPA, downlink spatial multiplexing is limited to two streams, corresponding to two transmit antennas at the network side and two receive antennas at the terminal side, often referred to as a 2×2 *antenna configuration*. In more details the HSPA spatial multiplexing scheme is a *pre-coder-based* scheme where the two streams to be transmitted, consisting of channel-coded, data modulated, and direct-sequence-spread information, are multiplied by a 2×2 pre-coder matrix before being mapped to the two transmit antennas. This can be seen as a generalization of the closed-loop transmit-diversity scheme supported already in the first release of WCDMA.

With two parallel streams, a doubling of the maximum data rate can be achieved. Thus, with spatial multiplexing in combination with 64QAM modulation, the evolution of HSPA supports downlink data rates up to 42 Mbps within a 5 MHz transmission bandwidth. It is important to understand though that such high data rates are only achievable in very good channel conditions with high signal-to-noise/interference ratios.

3.3 Continuous Packet Connectivity

To further improve the provisioning of packet-data services, a set of features jointly known as *Continuous Packet Connectivity* (CPC) has also been introduced as part of the evolution of HSPA. CPC consists of three primary building blocks

- *Uplink discontinuous transmission*
- *Downlink discontinuous reception*
- *HS-SCCH-less operation*

Uplink discontinuous transmission (DTX) aims at reducing the uplink interference, thus improving system capacity, by reducing the duty cycle of the uplink layer-1 control channel (the so-called *Dedicated Physical Control Channel*, DPCCH). The DPCCH e.g. carries known pilot symbols to enable uplink channel estimation, and power-control commands for downlink power control. With uplink DTX, if no data is to be transmitted on the uplink the terminal disables continuous DPCCH transmission and instead begins periodic transmission according to a certain DTX cycle sufficient to ensure that the network can keep synchronization with the terminal. When data is to be transmitted, the terminal resumes continuous transmission of the DPCCH in order to e.g. enable accurate tracking of the channel variations at the receiver side.

In addition to a reduced interference level, leading to an improved system capacity, the possibility for uplink DTX also has a positive impact on the terminal battery life as a reduced duty cycle for uplink transmissions implies reduced terminal power consumption.

Downlink discontinuous reception (DRX) also aims at reducing the terminal power consumption by allowing for a terminal to receive on the downlink with a reduced duty cycle.

In normal (non-DRX) operation, downlink data transmission to a terminal can be scheduled in any subframe and, consequently, the terminal has to monitor the set of downlink control channels (the HS-SCCHs, see Sect. 2) in every subframe. The possibility to schedule a terminal in any subframe maximizes scheduling flexibility, which is beneficial from a system-performance point-of-view. At the same time, the corresponding need to continuously monitor a set of HS-SCCHs has a negative impact on the terminal power consumption. Downlink DRX implies that the terminal can only be scheduled on the downlink, and thus only has to monitor the HS-SCCHs, in a subset of the subframes. This allows for reduced terminal power consumption at the expense of a reduced scheduling flexibility.

In addition to downlink control information related to downlink data transmission there is also downlink control signaling related to *uplink* data transmission, such as uplink scheduling grants and hybrid-ARQ acknowledgements indicating correct reception of uplink data. When not receiving on the downlink, the terminal cannot receive this information. This will impose restrictions on the set of subframes in which uplink data transmission can take place in case of downlink DRX. Thus, in practice, downlink DRX is always operated in combination with uplink DTX.

As already mentioned, the set of HS-SCCH control channels carry information about what set of terminals are being scheduled on the downlink in a given subframe and what combination of channelization codes and transport format is used for the corresponding data transmission. For medium/high data rates, the overhead due to the HS-SCCH transmission is relatively small. However, for lower-rate services, such as Voice-over-IP (VoIP), the HS-SCCH overhead may not be insignificant. The possibility for *HS-SCCH-less operation* addresses this issue by allowing for downlink packet-data transmission without any accompanying HS-SCCH transmission. Instead, in case of HS-SCCH-less operation, the network configures the terminal with a set of pre-defined transmission formats that can be used for the downlink data transmission. In every subframe where downlink data transmission to the terminal can take place, the terminal tries to decode the received signal assuming the different configured formats, so called *blind decoding*. To reduce the decoding effort, the transmission configuration in case of HS-SCCH-less transmission is limited to QPSK modulation and at most two channelization codes. This is inline with the fact that any overhead reduction due to HS-SCCH-less operation is mainly beneficial in case of lower-rate services.

3.4 Latency Reduction and Protocol Enhancements

In WCDMA/HSPA, as in almost all mobile-communication systems, the terminal can be in different states depending on its activity. Typically, when the terminal has not been communicating with the network for some time, it is switched to a lower-activity state. Once there is data to be sent in either the downlink or the uplink direction, the terminal makes a transition back to the higher-activity state prior to data transmission. This state-handling mechanism saves terminal power as well as uplink interference, but the switching procedure will add to the latency experienced by the end-user. To address this, the evolution of HSPA include support for so-called *Enhanced CELL_FACH operation*. With Enhanced CELL_FACH operation, user-data transmission can start already during the state transition. This is especially important in order to provide an *always-on* experience for applications with regular but relatively infrequent transmission of small packets, e.g., different instant-messaging clients.

3.5 Dual-Carrier Operation

The latest step in the evolution of HSPA is *downlink dual-carrier operation*. In case of dual-carrier operation, the terminal can receive two adjacent 5 MHz HSPA carriers in parallel, effectively providing a 10 MHz downlink bandwidth and thus a possibility for further increase in the supportable downlink data rates.

4. LTE — The 3GPP Long-Term Evolution

In parallel to the work on HSPA and its evolution, 3GPP in 2004 initiated the work on *3GPP Long Term Evolution*, most often simply referred to as LTE. The aim of LTE was to take another step forward in terms of system performance and service capabilities and "*provide a smooth transition to 4G mobile communication*." In this section, an overview of the first release of LTE, also known as LTE release 8, will be given.

Compared to HSPA and its evolution LTE provides

- The possibility for wider transmission bandwidth up to 20 MHz for both downlink and uplink, in combination with a very high degree of bandwidth flexibility
- Support for both FDD and TDD operation, allowing for deployment in both paired and unpaired spectrum
- Support for more extensive multi-antenna transmission/reception, including downlink spatial multiplexing with up to four layers

The possibility for a wider transmission bandwidth, in combination with the support for higher-order downlink spatial multiplexing, enables LTE to provide downlink data rates up to 300 Mbps. In the uplink, data rates up to 75 Mbps are supported by LTE.

4.1 LTE — Basic Transmission Scheme

LTE downlink transmission is based on *Orthogonal Frequency Division Multiplexing* (OFDM) with a subcarrier spacing of 15 kHz. Due to the use of a large number of narrowband subcarriers transmitted in parallel, in combination with a cyclic prefix[†], OFDM transmission in inherently robust to radio-channel frequency selectivity. The use of OFDM transmission can thus avoid the need for advanced and relatively complex signal processing for channel equalization at the receiver side. This is more important for LTE, compared to WCDMA/HSPA, due to the possibility for a wider transmission bandwidth and higher-order spatial multiplexing in case of LTE.

In the uplink, LTE relies on so called *DFT-spread-OFDM* (DFTS-OFDM). As illustrated in Fig. 1, DFTS-OFDM can be seen as OFDM modulation preceded by DFT-based pre-coding. The size of the DFT precoder determines the instantaneous bandwidth of the transmitted signal and by adjusting the mapping from the output of the DFT to the input of the OFDM modulator, the transmitted signal can be shifted in the frequency domain, thus allowing for FDMA

[†]LTE supports two cyclic prefix, a *normal cyclic prefix* of length ≈ 4.7 μs and an *extended cyclic-prefix* of length ≈ 16.7 μs, with the extended cyclic prefix intended for highly frequency-selective channels.

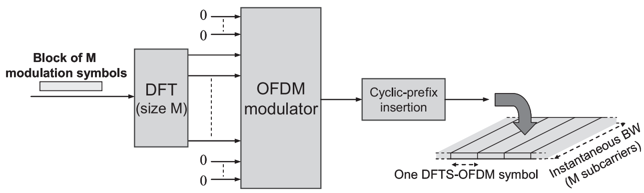

Fig. 1 Basic principle of DFTS-OFDM transmission.

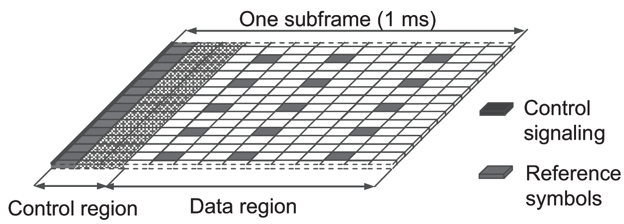

Fig. 2 LTE physical resource (downlink).

between uplink transmissions from different terminals.

Compared to conventional OFDM, DFTS-OFDM has significantly smaller variations in the instantaneous power of the transmitted signal, thus allowing for more efficient power-amplifier operation. This, in turn, allows for reduced terminal cost and power consumption. Alternatively, the higher power-amplifier efficiency can be utilized for higher terminal output power, leading to an increased range (larger cells) and/or the possibility for higher data rates at the cell border. Due to the small power variations, in combination with the possibility for FDMA between users, the LTE uplink transmission scheme is sometimes also referred to "Single-Carrier FDMA" (SC-FDMA).

The drawback of DFTS-OFDM transmission, compared to conventional non-precoded OFDM, is higher sensitivity to radio-channel frequency selectivity. As a consequence, to achieve good performance also in frequency-selective environments, DFTS-OFDM requires an equalizer at the receiver side. Thus, by using DFTS-OFDM for uplink transmission, the terminal complexity and power-consumption is reduced, and the range is improved, at the price of somewhat increased base-station receiver complexity. The most common receiver structure for DFTS-OFDM transmission is the still relatively low-complex frequency-domain linear equalizer [2]. However, more advanced receiver structures, e.g. based on Turbo equalization [3], can also be used.

4.2 Data Transmission and Control Signaling

The LTE downlink physical resource can be seen as a time/frequency grid as illustrated in Fig. 2.

Each downlink subframe of length 1 ms consists of two parts, a *control region* and a *data region*.

Transmission of user data takes place within the data region of the subframe. The overall radio resource is divided into so-called *resource blocks,* where each resource block consists of twelve subcarriers during one subframe. Within each subframe, a terminal can be scheduled data transmission on one or multiple resource blocks†.

Within the control region, different types of layer-1 and layer-2 (L1/L2) control signaling are transmitted. The L1/L2 control signaling conveys different types of control information including

- *Downlink scheduling assignments* providing information about the physical resource (the set of resource blocks) that is used for data transmission to a certain terminal within the subframe, as well as information about the transport format (modulation scheme, code rate, antenna pre-coding, etc.) used for the transmission
- *Uplink scheduling grants* providing information about the physical resource and transport format to be used for uplink data transmission from a terminal in a corresponding uplink subframe
- Hybrid-ARQ acknowledgements indicating correct decoding of uplink transmissions

The size of the control region is configurable from one to three OFDM symbols (up to four OFDM symbols in case of the most narrow system bandwidths) in order to be able to match the amount of resources available for the control signaling to different traffic scenarios.

Distributed within the time/frequency grid are known *reference symbols* to be used by the terminal e.g. for downlink channel estimation. In case of multi-antenna transmission, see below, there is one set of reference symbols transmitted from each antenna.

By transmitting the control signaling time multiplexed with, and preceding, the data transmission, the terminal can quickly determine if it is being scheduled within a subframe. If the terminal is not scheduled, it can disable reception for the remaining part of the subframe, thereby reducing terminal power consumption.

Uplink transmissions are scheduled by the base station for each 1 ms subframe. Similarly to the downlink, the uplink physical resource can be described as a time-frequency grid. However, as DFTS-OFDM is used, the resource blocks scheduled to a terminal are contiguous in frequency.

In the uplink, control signaling is used to send hybrid-ARQ acknowledgements, scheduling requests, and channel-status reports to aid the channel-dependent scheduling. Resource blocks at the band edges are used for this purpose as illustrated in Fig. 3 where intra-subframe frequency hopping provides the necessary frequency diversity.

4.3 Spectrum Flexibility

A high degree of spectrum flexibility is one key property of LTE, allowing for operation in a wide range of spectrum allocations with different size and duplex properties. The spectrum flexibility is also important to allow for a smooth

†There is a also a possibility to spread the transmission to a user over parts of multiple resource blocks, so called downlink *distributed transmission*.

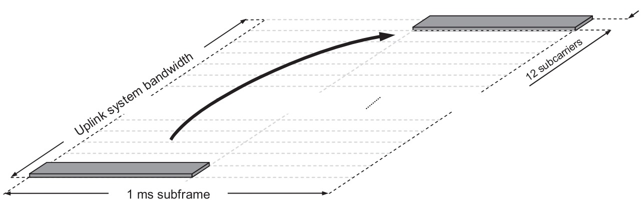

Fig. 3 Uplink control signaling.

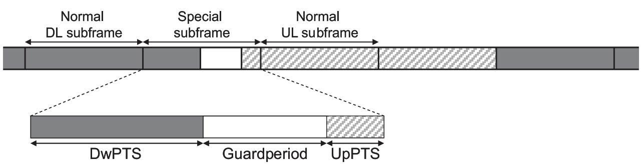

Fig. 4 Frame structure for LTE/TDD.

migration to LTE in spectrum already being used for other radio-access technologies, such GSM[†] or cdma2000/1xEV-DO[††].

In contrast to e.g. HSPA, LTE is not only able to operate in different frequency bands, such as 2 GHz, 2.6 GHz, 900 MHz, etc. but also with different system bandwidths. Fundamentally, the LTE physical-layer specification provides very high bandwidth flexibility by allowing for any system bandwidth corresponding to an integer number of resource blocks. However, radio-performance requirements are only defined for a limited set of bandwidths, currently 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz, which is thus the set of system bandwidths currently supported by LTE. The benefit of having a physical-layer specification that supports a much larger set of bandwidths is that support for *additional* system bandwidths is straightforward to introduce, should a need occur, by simply defining additional radio-performance requirements while not requiring any updates to the core physical-layer specifications.

In addition to being able to operate in spectrum of different size, LTE is also able to operate in both *paired* and *unpaired* spectrum, due to the support for both *Frequency-Division Duplex* (FDD) and *Time-Division Duplex* (TDD) operation. The transmission schemes for FDD and TDD in LTE have a high-degree of commonality also in the details, allowing for a low incremental cost to design and implement terminals supporting both FDD and TDD operation. One difference between FDD and TDD is the presence of a *special subframe* within the TDD frame structure, providing the downlink/uplink guard time needed for proper TDD operation. As illustrated in Fig. 4, the special subframe consists of a *downlink part* (DwPTS), a *guard period*, and an *uplink part* (UpPTS) with the lengths of the different fields being configurable in order to allow for optimization for different deployment scenarios such as different cell sizes. The configurability of the special subframe also allows for good alignment with the frame structure of

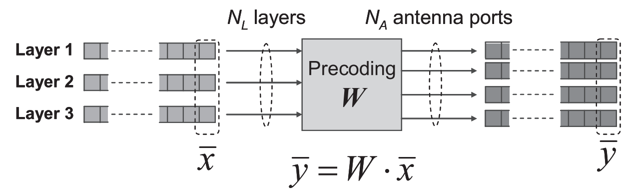

Fig. 5 LTE pre-coder-based spatial multiplexing. Number of layers N_L = 3.

the TD-SCDMA[†††] 3G radio-access technology. The possibility for such an alignment is important in order to ensure efficient co-existence between LTE/TDD and TD-SCDMA. LTE/TDD allows for a range of different downlink/uplink asymmetries, ranging from a 9:1 asymmetry (nine downlink subframes and one uplink subframe within one 10 ms frame) to a 2:3 asymmetry (4 downlink subframes and six uplink subframes within a frame).

4.4 Multi-Antenna Transmission in LTE

Downlink multi-antenna transmission, including both transmit diversity and spatial multiplexing, is supported already in later releases of HSPA. However, LTE takes downlink multi-antenna transmission a step further by introducing support for more extensive antenna configurations (additional transmit and receive antennas) as well as providing a more rich set of multi-antenna transmission schemes. More specifically, LTE downlink multi-antenna transmission supports up to four antenna ports[††††] and includes transmission modes for *transmit diversity*, *spatial multiplexing*, and different *beam-forming* solutions.

LTE transmit diversity is based on so-called *Space-Frequency Block Coding* (SFBC), complemented with *Frequency Switched Transmit Diversity* (FSTD) in case of four antenna ports. Two-antenna SFBC is similar to Space-Time Transmit Diversity (STTD) as used for WCDMA/HSPA with the main difference being that the antenna coding is done in the frequency domain, rather than in the time domain. Combined SFBC/FSTD, used in case of four antenna ports, implies that pairs of modulation symbols are transmitted by means of SFBC, with transmission alternating between pairs of antenna ports.

Similar to HSPA, LTE relies on *pre-coder*-based spatial multiplexing, see Fig. 5. A number of transmission layers (three layers in Fig. 5) are mapped to up to four antenna ports by means of a precoder matrix $\boldsymbol{W}$ 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 antenna ports N_A. The transmission rank, as well as the exact pre-

[†] Global System for Mobile communication.

[††] 1x EVolution Data-Only.

[†††] Time Division Synchronous Code Division Multiple Access.

[††††] The LTE specification talks about *antenna ports*, rather than antennas, to indicate that what the UE sees as an antenna may, in practice, consist of several physical antennas. Fundamentally, an antenna port corresponds to the transmission of a unique set of reference symbols.

coder matrix, is selected by the network and can be dynamically varied based e.g. on channel-status measurements carried out and reported by the terminal, so-called *closed-loop spatial multiplexing*. The network then explicitly informs the terminal about the selected rank and pre-coder matrix as part of the downlink scheduling assignment. Alternatively, the pre-coder matrix to use in a subframe is pre-determined, so-called "*open-loop spatial multiplexing*."

In case of spatial multiplexing, by selecting rank-1 transmission, corresponding to transmission of a single layer, the precoder matrix performs a (single-layer) *beam-forming* function. This type of beam-forming can be referred to as *codebook-based* beam-forming as the beam-forming is done according to a limited set of pre-defined beam-forming vectors (the set of available pre-coder matrices of size $N_A \times 1$). In case of code-book-based beam-forming, the terminal can rely on the (cell-specific) reference symbols, in combination with knowledge of the applied beam-forming vector, for coherent detection of the beam-formed data transmission.

In addition to codebook-based beam-forming, LTE also supports *non-codebook-based beam-forming* where the network can apply any beam-forming vector and does not inform the terminal what vector has been applied. In contrast to codebook-based beam-forming, the terminal then needs an estimate of the overall beam-formed channel in order to detect the beam-formed data transmission. To enable this, LTE allows for the transmission of additional terminal-specific ("*UE-specific*") reference symbols within the resource blocks scheduled for a terminal. The UE-specific reference symbols are transmitted using the same beam-forming vector as is applied for the data transmission and can thus be used by the terminal to estimate the overall beam-formed channel. Non-codebook-based beam-forming is especially applicable to LTE/TDD as the downlink/uplink channel reciprocity inherent in TDD operation can be utilized by the network when selecting the beam-forming vector.

4.5 Inter Cell Interference Coordination (ICIC)

In LTE, both the uplink and the downlink transmission schemes are *orthogonal* implying that there is, at least in principle, no interference between transmissions within the same cell but only interference between cells. This makes suppression of interference between cells ("inter-cell interference") an important tool for improved system performance and in particular increased cell-edge data rates. Uplink power control is one mechanism that can be used for this purpose. Power control is not only used to control the received signal strength in the intended cell, but also to control the amount of interference caused to neighboring cells. LTE uplink power control supports *fractional pathloss compensation*, implying that terminals close to the cell border use relatively less transmit power and thus generate relatively less interference to neighbor cells.

Different scheduling strategies can also be used to control the inter-cell interference in both the 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 the use of a frequency reuse larger than one. Such schemes improve the signal-to-interference ratios for the available frequencies. However, the loss due to reduced bandwidth availability is typically larger than the corresponding gain due to higher SIR, leading to an overall loss of system performance. The LTE standard therefore provides tools for coordinating the scheduling in neighbor cells such that cell-edge users in different cells are *preferably* scheduled on complementary parts of the spectrum *when needed*, thereby reducing the inter-cell interference experienced by cell-edge users. Note that, in contrast to a static frequency-reuse larger than one, this kind of inter-cell interference coordination still allows for the total available spectrum to be used in all cells. Bandwidth restrictions are only applied when traffic and radio conditions so requires.

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. In the downlink, on the other hand, the interference originates from 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 may be more suited for the uplink. Also, as the LTE interference-coordination mechanism is based on scheduling restrictions in the frequency domain, it is mainly suited for relatively narrow-band 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 narrow-band than downlink transmissions. Also this indicates that inter-cell interference coordination may be more beneficial for 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. As cell-edge users are susceptible to inter-cell interference, upon receiving the high-interference indicator, a neighbor cell may try to avoid scheduling certain subsets of its own users on this part of the bandwidth. This subset includes users close to the cell issuing 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, e.g., by using a different set of resources, and, in this way, improve the interference situation for the neighbor cell issuing 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 but, 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 its transmission power. A cell receiving the indication may schedule its downlink transmissions within this band, reducing the output power or completely free resources on complementary parts of the spectrum.

4.6 Future Support for Multicast/Broadcast Services

OFDM transmission has special benefit for the provisioning of multicast/broadcast services, i.e. when the same data is to be provided to many users distributed over multiple neighbor cells. In that case, by transmitting identical signals from the set of cells from which the multicast/broadcast service is to be provided and having the mobile terminals receive the overall signal, a significantly improved SINR, and correspondingly higher multicast/broadcast data rates can be achieved. The first release of LTE does not support such MBSFN (Multicast Broadcast Single Frequency) operation. However, LTE is prepared for a backwards-compatible introduction of MBSFN transmission of multicast/broadcast services in later releases by supporting the configuration of so-called *MBSFN subframes* in which no unicast user data and only a more limited set of reference symbols are being transmitted.

5. LTE Evolution towards IMT-Advanced

Although LTE was explicitly intended to provide a smooth transition to 4G radio access, the first release of LTE is still formally part of the *IMT-2000* family of radio-access technologies defined by ITU† [4]. However, in April 2008, ITU issued a circular letter inviting submissions of candidates for *IMT-Advanced* [5]. IMT-Advanced is the next major step within ITU in terms of radio-access technologies for mobile communication. Similar to IMT-2000 being associated with 3G mobile communication, IMT-Advanced is often seen as corresponding to so-called *4G radio access*.

Partly as a response to the ITU request, 3GPP has initiated a study item on the evolution of LTE, an evolution also referred to as *LTE-Advanced* [6]. The aim of this study item is to study candidate technology components for the evolution of LTE towards LTE-Advanced.

The requirements for IMT-Advanced defined in [7]. Some of the requirements of IMT-Advanced are outlined in Table 1, together with the corresponding characteristics of the first release of LTE and the agreed targets for LTE-Advanced [8]. As can be seen, the first release of LTE already fulfills or is close to fulfill most of the requirements of IMT-Advanced, with the maximum-bandwidth requirements and uplink peak-spectral efficiency being the main exceptions. As can also be seen, in most cases the targets for LTE-Advanced significantly exceed the corresponding requirements for IMT-Advanced. Thus LTE-Advanced will not only take LTE towards, but actually beyond, IMT-Advanced.

Table 1 Requirements for IMT-Advanced vs. current LTE and the targets for LTE-Advanced.

	IMT-Advanced	Current LTE	LTE-Advanced
Maximum bandwidth	*40 MHz*	*20 MHz*	*100 MHz*
Peak spectral eff. - *Downlink*[1] - *Uplink*[2]	 *15 bps/Hz* *6.75 bps/Hz*	 *15 bps/Hz* *3.75 bps/Hz*	 *30 bps/Hz* *15 bps/Hz*
Average spectral eff. - *Downlink*[1] - *Uplink*[2]	 *2.2 bps/Hz* *1.4 bps/Hz*	 *2.05 bps/Hz* *1.5 bps/Hz*	 *2.6 bps/Hz* *2.0 bps/Hz*
Cell-edge spectral eff. - *Downlink*[1] - *Uplink*[2]	 *0.06 bps/Hz* *0.03 bps/Hz*	 *0.06 bps/Hz* *0.07 bps/Hz*	 *0.09 bps/Hz* *0.07 bps/Hz*

[1] Downlink antenna configuration: 4×2.
[2] Uplink antenna configuration: 2×4 for IMT/LTE-Advanced, 1×4 for LTE.

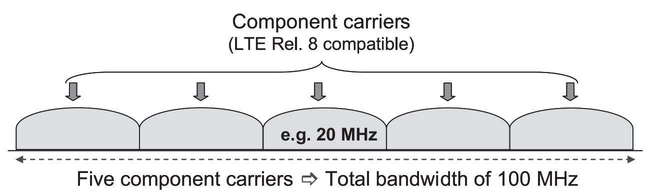

Fig. 6 Carrier aggregation for extended bandwidth.

At the time of writing, the technology components to be included as part of the LTE evolution towards LTE-Advanced are still very much under discussion. However, certain technology components are frequently mentioned in this context and it can be expected that these will, in some form or another, eventually be part of LTE-Advanced.

5.1 Carrier/Spectrum Aggregation

The very high data rates targeted by LTE-Advanced can only be efficiently supported by extending the maximum system bandwidth beyond the 20 MHz of the first release of LTE. To achieve such a bandwidth extension, while still preserving backwards compatibility, *carrier aggregation* will be used. As illustrated in Fig. 6, carrier aggregation implies that the extension to wider bandwidth is achieved by aggregating multiple *component carriers* where each component carrier can appear as an LTE release 8 carrier to LTE release 8 terminals. Thus, an LTE release 8 terminal can access the system using one of the component carriers while LTE-Advanced-capable terminals can communicate using multiple carriers in parallel, thus benefiting from an overall wider bandwidth and a corresponding possibility for higher data rates.

Figure 6 illustrates the aggregation of *frequency-*

†International Telecommunication Union.

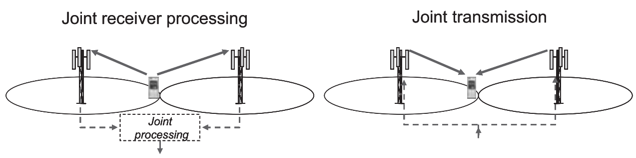

Fig. 7 Coordinated multipoint transmission/reception based on joint uplink receiver processing and joint downlink transmission, respectively.

adjacent component carriers, which would be the typical case. However, in the general case one could aggregate also *frequency-separate* component carriers, including even carriers in separate frequency bands. Such *spectrum aggregation* provides a means to achieve an overall wider bandwidth even if very large contiguous frequency blocks are not available. It is understood though that such general spectrum aggregation would have a negative impact on terminal complexity and can thus only be expected to be supported by higher-end terminals.

5.2 Extended Multi-Antenna Transmission

The first release of LTE supports four-layer downlink spatial multiplexing, typically assuming a 4×4 antenna configuration. To achieve the downlink peak-spectral efficiency targets of LTE-Advanced (30 bps/Hz), even higher-order spatial multiplexing is required. Thus, in order to fulfill the targets, LTE-Advanced should include extended downlink spatial multiplexing supporting up to eight layers (8×8 antenna configuration). Furthermore, in order to satisfy the uplink peak-spectral-efficiency targets, LTE-Advanced should also support uplink spatial multiplexing. As an example, four-layer uplink spatial multiplexing is needed to achieve an uplink peak spectral efficiency of 15 bps/Hz, assuming 16QAM modulation.

5.3 Coordinated Multipoint Transmission/Reception

Coordinated multipoint transmission/reception, also referred to as CoMP, is one technology considered in the context of LTE-Advanced.

The basic principle of CoMP is to apply *dynamic coordination* of the transmission and/or reception *at different cells sites*. The coordination can be in different forms. One possibility is to dynamically coordinate the scheduling between different cell sites, in essence a kind of more dynamic inter-cell interference coordination. More advanced CoMP could include:

- Reception and joint processing of uplink signals received at multiple cells sites (left part of Fig. 7)
- Joint transmission to a terminal from multiple cell sites in the downlink (right part of Fig. 7)

In general, the aim of CoMP is to reduce/control the inter-cell interference and/or improve the received signal strength. In this way, system performance can be improved and the service quality enhanced especially for users at the

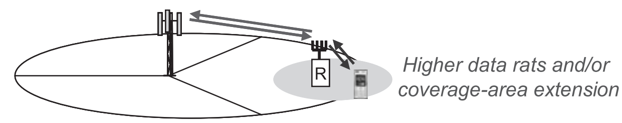

Fig. 8 Repeater/relaying functionality.

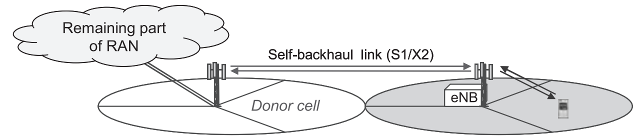

Fig. 9 Self-backhauling.

cell border. The main challenge of CoMP is the additional network-internal signaling that could be needed to realize the coordination between cell sites. This is especially the case for joint transmission and/or reception as outlined in Fig. 7.

5.4 Relaying Functionality

Different types of relaying functionality is another technology component frequently discussed within the context of LTE-Advanced. As illustrated in Fig. 8, the aim of relaying is to improve the cell coverage, either in terms of an extended coverage area (larger cell size) or a possibility for higher data rates within the cell, by introducing a "relay" nodes that forward the transmission to/from the mobile terminal.

Within the context of relaying, one can distinguish between different relaying approaches depending on what layer the relaying is taking place on.

A Layer-1 relay, also known as a repeater, carries out amplify-and-forward processing, i.e. forwards the transmission on layer 1. A Layer-1 relay is characterized by a low delay and can be more or less advanced, including e.g. the possibility for power control, time- and/or frequency-selective repetition, and multi-antenna support. It should be noted that a simple amplify-and-forward relay is essentially invisible to the UE, implying that it can be introduced with no impact on the radio-access specification.

Layer-2 and Layer-3 relay carries out *decode-and-forward* processing, i.e. forward the transmission on layer 2 or layer 3. Compared to Layer-1 relaying (a repeater), Layer-2/3 relaying implies additional delay, as the transmission needs to be decoded and re-encoded within the relay. On the other hand, the decoding/re-encoding provides a possibility for an SINR improvement in the relaying, something which is not possible in case of the amplify-and-forwarding of a Layer 1 relay.

A special case of relaying functionality is the use of *self-backhauling* solutions. Self-backhauling implies that the backhaul link to the cell site is provided by means of the LTE-Advanced radio access operating within the IMT band. As illustrated in Fig. 9, the self-backhauling link originates from a *donor cell* that provides the connection to the remaining part of the radio-access network.

Characterizing for a self-backhauling solution is that the “relay” node provides full eNB functionality. Thus, the cells of the self-backhauled eNB will be fully accessible by all LTE terminals, not only LTE-Advanced-capable terminals.

6. Conclusion

This paper has provided an overview of HSPA and LTE, which rapidly have emerged as the leading technologies for providing mobile broadband. The evolution of LTE into LTE-Advanced in order to fulfill and surpass the IMT-Advanced requirements has also been outlined. Undoubtedly will these technologies continue to be evolved to provide operators with the tools to meet future requirements on mobile broadband.

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