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Research Article

On the Way towards Fourth-Generation Mobile: 3GPP LTE and LTE-Advanced

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Long-Term Evolution (LTE) is the new standard recently specified by the 3GPP on the way towards fourth-generation mobile. This paper presents the main technical features of this standard as well as its performance in terms of peak bit rate and average cell throughput, among others. LTE entails a big technological improvement as compared with the previous 3G standard. However, this paper also demonstrates that LTE performance does not fulfil the technical requirements established by ITU-R to classify one radio access technology as a member of the IMT-Advanced family of standards. Thus, this paper describes the procedure followed by the 3GPP to address these challenging requirements. Through the design and optimization of new radio access techniques and a further evolution of the system, the 3GPP is laying down the foundations of the future LTE-Advanced standard, the 3GPP candidate for 4G. This paper offers a brief insight into these technological trends.

1. Introduction

In the last years, technology evolution in mobile communications is mainly motivated by three relevant agents: (1) the market globalization and liberalization and the increasing competence among vendors and operators coming from this new framework, (2) the popularization of IEEE 802 wireless technologies within the mobile communications sector and, finally, (3) the exponential increase in the demand for advanced telecommunication services.

Concerning the last item, the envisaged applications to be supported by current and future cellular systems include Voice over IP (VoIP), videoconference, push-to-talk over cellular (PoC), multimedia messaging, multiplayer games, audio and video streaming, content download of ring tones, video clips, Virtual Private Network (VPN) connections, web browsing, email access, File Transfer Protocol (FTP). All these applications can be classified in several ways based on the Quality of Service (QoS) treatment that they require. Some of them are real-time and delay-sensitive, like voice and videoconference, while some others require integrity, high data-rate, and are sensitive to latency (like VPN and FTP). The simultaneous support of applications with different QoS requirements is one of the most important challenges that cellular systems are facing. At the same time, the spectrum scarcity makes that new wideband cellular systems are designed with very high spectral efficiency.

It is precisely that this increasing market demand and its enormous economic benefits, together with the new challenges that come with the requirements in higher spectral efficiency and services aggregation, raised the need to allocate new frequency channels to mobile communications systems. That is why the ITU-R WP 8F started in October 2005 the definition of the future Fourth-Generation Mobile (4G), also known as International Mobile Telecommunications (IMTs) Advanced, following the same model of global standardization used with the Third Generation, IMT-2000. The objective of this initiative is to specify a set of requirements in terms of transmission capacity and quality of service, in such a way that if a certain technology fulfils all these requirements it is included by the ITU in the IMT-Advanced set of standards. This inclusion firstly endorses technologies and motivates operators to invest in them, but furthermore it allows these standards to make use of the frequency bands specially designated for IMT-Advanced, what entails a great motivation for mobile operators to increase their offered services and transmission capacity.

The race towards IMT-Advanced was officially started in March 2008, when a Circular Letter was distributed asking for the submission of new technology proposals [1]. Previous to this official call, the 3rd Partnership Project (3GPP) established the Long Term Evolution (LTE) standardization activity as an ongoing task to build up a framework for the evolution of the 3GPP radio technologies, concretely UMTS, towards 4G. The 3GPP divided this work into two phases: the former concerns the completion of the first LTE standard (Release 8), whereas the latter intends to adapt LTE to the requirements of 4G through the specification of a new technology called LTE-Advanced (Release 9 and 10). Following this plan, in December 2008 3GPP approved the specifications of LTE Release 8 which encompasses the Evolved UTRAN (E-UTRAN) and the Evolved Packet Core (EPC). Otherwise, the LTE-Advanced Study Item was launched in May 2008, expecting its completion in October 2009 according to the ITU-R schedule for the IMT-Advanced process. In the meantime, research community has been called for the performance assessment of the definitive LTE Release 8 standard.

Actually, several papers deal with the performance evaluation of LTE. However, up to date this assessment has been partially done because of one of these two reasons. First, some of these works only focused on the physical layer, leaving out the retransmission processes and error correction [2–4]. System level analysis needs MAC layer performance information and cannot be carried out with only a physical layer characterization. Second, other papers assessing the performance of LTE radio access network assumed ideal channel estimation, which results in an optimistic estimation of LTE capacity [5–7].

This paper describes the main characteristics of LTE Release 8 and evaluates LTE link level performance considering a transmission chain fully compliant with LTE Release 8 and including realistic HARQ and turbo-decoding. Besides, the capacity of LTE systems is analyzed in terms of maximum achievable throughput and cell capacity distribution in a conventional scenario. These studies allow having a rough idea on the benefits and capabilities of the new standard. Finally, this paper offers an overview of the current research trends followed by 3GPP in the definition process of LTE-Advanced thus foreseeing the main characteristics of next generation mobile.

2. LTE

3GPP Long Term Evolution is the name given to the new standard developed by 3GPP to cope with the increasing throughput requirements of the market. LTE is the next step in the evolution of 2G and 3G systems and also in the provisioning of quality levels similar to those of current wired networks.

3GPP RAN working groups started LTE/EPC standardization in December 2004 with a feasibility study for an evolved UTRAN and for the all IP-based EPC. This is known as the Study Item phase. In December 2007 all LTE functional specifications were finished. Besides, EPC functional specifications reached major milestones for interworking with 3GPP and CDMA networks. In 2008 3GPP working groups were running to finish all protocol and performance specifications, being these tasks completed in December 2008 hence ending Release 8.

2.1. LTE Requirements. 3GPP collected in [8] the requirements that an evolved UTRAN should meet. Some of the requirements are defined in an absolute manner while other requirements are defined in relation to UTRA performance. It is worth to mention that for the UTRA baseline it is considered the use of Release 6 HSDPA with a $\mathbf{1} \times \mathbf{1}$ multiantenna scheme for the downlink and Release 6 HSUPA with a $\mathbf{1} \times \mathbf{2}$ multiantenna scheme in uplink. For the sake of comparison, in LTE it is considered transmission using up to $\mathbf{2} \times \mathbf{2}$ antennas in downlink and up to $\mathbf{1} \times \mathbf{2}$ antennas in uplink.

Among others, LTE design targets are the following.

(i) The system should support peak data rates of 100 Mbps in downlink and 50 Mbps in uplink within a 20 MHz bandwidth or, equivalently, spectral efficiency values of 5 bps/Hz and 2.5 bps/Hz, respectively. Baseline considers 2 antennas in UE for downlink and 1 antenna in UE for uplink.

(ii) Downlink and uplink user throughput per MHz at the 5% point of the CDF, 2 to 3 times Release 6 HSPA.

(iii) Downlink averaged user throughput per MHz, 3 to 4 times Release 6 HSDPA. Uplink averaged user throughput per MHz, 2 to 3 times Release 6 Enhanced Uplink.

(iv) Spectrum efficiency 3 to 4 times Release 6 HSDPA in downlink and 2 to 3 times Release 6 HSUPA in uplink, in a loaded network.

(v) Mobility up to 350 km/h.

(vi) Spectrum flexibility, seamless coexistence with previous technologies and reduced complexity and cost of the overall system.

2.2. LTE Release 8 Technical Overview. To meet these requirements, a combination of a new system architecture together with an enhanced radio access technology was incorporated in the specifications.

2.2.1. Architecture. There are different types of functions in a cellular network. Based on them, network can be split into two parts: a radio access network part and a core network part. Functions like modulation, header compression and handover belong to the access network, whereas other functions like charging or mobility management are part of the core network. In case of LTE, the radio access network is E-UTRAN and the core network EPC.

Radio Access Network. The radio access network of LTE is called E-UTRAN and one of its main features is that all services, including real-time, will be supported over shared packet channels. This approach will achieve increased spectral efficiency which will turn into higher system capacity with respect to current UMTS and HSPA. An important consequence of using packet access for all services is the better integration among all multimedia services and among wireless and fixed services.

The main philosophy behind LTE is minimizing the number of nodes. Therefore the developers opted for a single-node architecture. The new base station is more complicated than the Node B in WCDMA/HSPA radio access networks, and is consequently called eNB (Enhanced Node B). The eNBs have all necessary functionalities for LTE radio access network including the functions related to radio resource management.

Core Network. The new core network is a radical evolution of the one of third generation systems and it only covers the packet-switched domain. Therefore it has a new name: Evolved Packet Core.

Following the same philosophy as for the E-UTRAN, the number of nodes is reduced. EPC divides user data flows into the control and the data planes. A specific node is defined for each plane plus the generic gateway that connects the LTE network to the internet and other systems. The EPC comprises several functional entities.

(i) The MME (Mobility Management Entity): is responsible for the control plane functions related to subscriber and session management.

(ii) The Serving Gateway: is the anchor point of the packet data interface towards E-UTRAN. Moreover, it acts as the routing node towards other 3GPP technologies.

(iii) The PDN Gateway (Packet Data Network): is the termination point for sessions towards the external packet data network. It is also the router to the Internet.

(iv) The PCRF (Policy and Charging Rules Function): controls the tariff making and the IP Multimedia Subsystem (IMS) configuration of each user.

The overall structure of LTE is shown in Figure 1.

2.2.2. Radio Access Fundamentals. The most important technologies included in the new radio access network are Orthogonal Frequency Division Multiplexing (OFDM), multidimensional (time, frequency) dynamic resource allocation and link adaptation, Multiple Input Multiple Output (MIMO) transmission, turbo coding and hybrid Automatic Repeat reQuest (ARQ) with soft combining. These technologies are shortly explained in the following paragraphs.

OFDM. Orthogonal Frequency Division Multiplexing is a kind of multicarrier transmission technique with a relatively large number of subcarriers. OFDM offers a lot of advantages. First of all, by using a multiple carrier transmission technique, the symbol time can be made substantially longer than the channel delay spread, which reduces significantly or even removes the intersymbol interference (ISI). In other words, OFDM provides a high robustness against frequency selective fading. Secondly, due to its specific structure, OFDM allows for low-complexity implementation by means of Fast Fourier Transform (FFT) processing. Thirdly, the access to the frequency domain (OFDMA) implies a high degree of freedom to the scheduler. Finally, it offers spectrum flexibility which facilitates a smooth evolution from already existing radio access technologies to LTE.

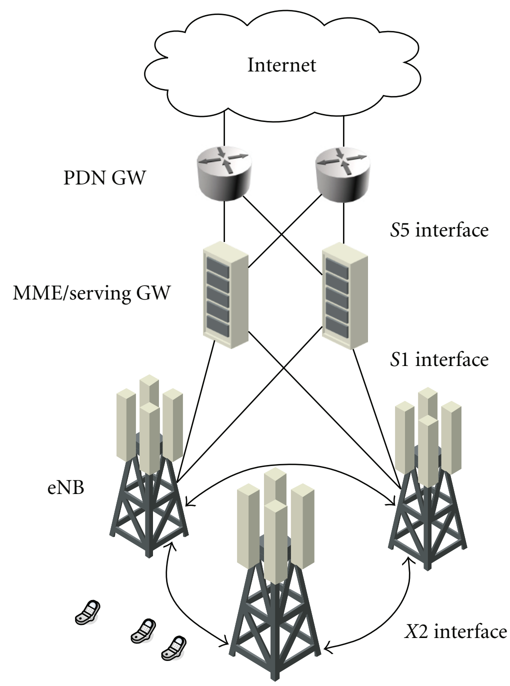

Figure 1: LTE Release 8 architecture.

In the FDD mode of LTE each OFDM symbol is transmitted over subcarriers of 15 or 7.5 kHz. One subframe lasts 1 ms, divided in two 0.5 ms slots, and contains several consecutive OFDM symbols (14 and 12 for the 15 and 7.5 kHz modes, resp.).

In the uplink, Single Carrier Frequency Division Multiple Access (SC-FDMA) is used rather than OFDM. SC-FDMA is also known as DFT-spread OFDM modulation. Basically, SC-FDMA is identical to OFDM unless an initial FFT is applied before the OFDM modulation. The objective of such modification is to reduce the peak to average power ratio, thus decreasing the power consumption in the user terminals.

Multidimensional Dynamic Resource Allocation and Link Adaptation. In LTE, both uplink and downlink transmission schemes can assign smaller, nonoverlapping frequency bands to the different users, offering frequency division multiple access (FDMA). This assignment can be dynamically adjusted in time and is referred to as scheduling. Accordingly, the LTE resources can be represented as a time-frequency grid. The minor element of this grid is called resource element and consists of one subcarrier during an OFDM symbol. However, the minor LTE resource allocation unit is the resource block that consists of 12 subcarriers during one slot.

Link adaptation is closely related to scheduling and deals with how to set the transmission parameters of a radio link to handle variations of the radio-link quality. This is achieved in LTE through adaptive channel coding and adaptive modulation. Specifically, in LTE available modulations are QPSK, 16QAM and 64QAM, whilst coding rate can take values from a lower edge of around 0.07 up to 0.93.

MIMO. One of the most important means to achieve the high data rate objectives for LTE is multiple antenna transmission. In LTE downlink it is supported one, two or four transmit antennas in the eNB and one, two or four receive antennas in the UE. Multiple antennas can be used in different ways: to obtain additional transmit/receive diversity or to get spatial multiplexing increasing the data rate by creating several parallel channels if conditions allow to. Nevertheless, in LTE uplink although one, two or four receive antennas are allowed in the eNB, only one transmitting antenna is allowed in the UE. Therefore, multiple antennas can be only used to obtain receive diversity.

Turbo Coding. In order to correct bit errors, introduced by channel variations and noise, channel coding is utilized. In case of the LTE downlink shared channel (DL-SCH) a turbo encoder with rate 1/3 is used, followed by a rate matching to adapt the coding rate to the desired level. In each subframe of 1 ms, one or two (with multicodeword MIMO) codewords can be coded and transmitted.

Hybrid ARQ with Soft Combining. Hybrid ARQ with soft combining is a technique that deals with the retransmission of data in case of errors. In an ARQ scheme, the receiver uses an error-detecting code to check if the received packet contains errors or not. The transmitter is informed by a NACK or ACK respectively. In case of a NACK, the packet is retransmitted.

A combination of forward error correction (FEC) and ARQ is known as hybrid ARQ. Most practical hybrid ARQ schemes are built around a CRC code for error detection and a turbocode for error correction, as it is the case of LTE.

In hybrid ARQ with soft combining, the erroneously received packet is stored in a buffer and later combined with the retransmission(s) to obtain a single packet that is more reliable than its constituents. In LTE full incremental redundancy (IR) is applied, which means that the retransmitted packets are typically not identical with the first transmission but carry complementary information.

2.3. Analysis of LTE Performance. Different methods can be used to assess the performance of a mobile technology. Each method is best suited for a particular kind of performance assessment. For instance, analytical methods or inspections are valid to evaluate peak data rates or peak spectral efficiencies. However, a deeper performance analysis requires the usage of simulation. Simulators are usually divided in two classes: link level simulators and system level simulators. Link level simulators are used to emulate the transmission of information from a unique transmitter to a unique receiver modeling the physical layer with high precision. They include models for coding/decoding, MIMO processing, scrambling, modulation, channel, channel estimation and equalization, and so forth. System level simulators emulate the operation of a network with a number of cells and several users per cell. In this kind of simulators, higher level functions are included for call admission control, scheduling, power control, and so forth, while link to system level models is used to facilitate the emulation of each radio link. This section presents some results obtained from both types of simulators.

In the course of the LTE standardization process, the 3GPP conducted several deep evaluations of the developing technology to ensure the achievement of requirements. With this aim, a feasibility study for E-UTRA and E-UTRAN was carried out in the 3GPP. Reference framework for the performance analysis is set by two documents [9, 10], to ensure the comparability of the different results. Mean LTE performance results obtained by the 3GPP partners are included in [11] where the results are also compared to the requirements. Results shown in that document are a summary of those in [12, 13] that collect the results of all the partners. In this assessment the used scenarios are similar to those used by the 3GPP to allow comparability of results.

This assessment allows getting an insight into to which extent LTE implies a revolution in comparison with UMTS. As shown in next section, LTE results demonstrate that this technology is quite close to the requirements established for the Fourth-Generation mobile, although further improvements are expected in LTE-Advanced.

2.3.1. Peak Spectral Efficiency. The peak spectral efficiency is the highest theoretical data rate assignable to a single mobile user divided by the allocated bandwidth. The highest data rate is calculated as the received data bits assuming error-free conditions and excluding radio resources that are used for control issues and guard bands. At the end, the radio access technology is classified as more or less powerful according to the achievable efficiency what makes this measurement perfect for comparative purposes.

Assuming a transmission bandwidth of 20 MHz the maximum achievable rates in downlink are: 91.2 Mbps for SIMO 1×2, 172.8 Mbps for MIMO 2×2 and 326.4 Mbps for MIMO 4×4. The resulting peak spectral efficiencies are 4.56, 8.64 and 16.32 b/s/Hz for the considered multiantenna schemes. These values have been calculated taking into account realistic overhead due to the reference signals and assuming that control signals overhead is equal to one OFDM symbol in each subframe. In uplink with SIMO 1×2 the maximum achievable rate is 86.4 Mbps with a transmission bandwidth of 20 MHz. Thus, the peak spectral efficiency is 4.32 b/s/Hz. These values have been calculated assuming that two OFDM symbols are occupied by reference signals. Both in downlink and uplink calculations 64QAM is the considered modulation and code rate is assumed to be 1.

The calculated peak spectral efficiencies of LTE are depicted in Figure 2 for both downlink and uplink together with the efficiencies of UMTS Release 6, that is, including HSDPA and HSUPA. From this peak spectrum efficiency it can be seen that LTE with 20 MHz meets and exceeds the 100 Mbps downlink and 50 Mbps uplink initial targets. Besides, the comparison with UMTS demonstrates that LTE is a major step forward in mobile radio communications. With these achievable data rates mobile systems will give a greater user experience with the capability of supporting more demanding applications.

2.3.2. LTE Link Level Performance. Based on link level simulations it can be assessed the relation between effective throughput (correctly received bits per time unit) and signal-to-noise plus interference ratio (SINR). Simulations assessed for this paper used 10 MHz of bandwidth for both downlink and uplink. This bandwidth is equivalent to 50 LTE resource blocks. The evaluation was focused on the performance experienced by a pedestrian user and hence the user mobility model used was the extended pedestrian A model [14] with a Doppler frequency of 5 Hz. The central frequency has been set to 2.5 GHz, the most likely band for initial LTE deployment. The set of modulation and coding schemes has been selected from the CQI table included in LTE specifications [15]. This set was selected by 3GPP to cover the LTE SINR dynamic margin with approximately 2 dB steps between consecutive curves. A distinction from other studies is that channel estimation was realistically calculated at the receivers. In order to exploit the multiantenna configuration at the receiver side, minimum mean-square error (MMSE) equalization was considered. The remaining parameters considered in the simulations are summarized in Table 1.

Concerning LTE downlink, different multiantenna configurations were modeled including SIMO 1×2, MIMO 2×2 and MIMO 4×4. Simulated MIMO scheme followed the open loop spatial multiplexing scheme as specified by the 3GPP [16], the number of codewords was 2 and the number of layers was equal to the number of transmit antennas, that is, 2 and 4. Additionally, the multiple channels among antennas were supposed uncorrelated. Control channel and signals overhead were taken into account and hence the first two OFDM symbols in each subframe were reserved for control channels. Besides, reference signals were emulated in detail, although neither broadcast information nor synchronization signals overhead was considered.

In the uplink, two different multiantenna configurations were simulated: SIMO 1×2 and SIMO 1×4. The multiple channels among antennas were supposed uncorrelated too. Nowadays, the LTE standard does not allow MIMO in uplink so that MIMO schemes were not simulated. Therefore, as established in the 3GPP specifications [17], only one codeword was considered. Moreover, 12 of the 14 available SC-FDMA symbols in a subframe were occupied by codified data since the other 2 were reserved for reference signals needed for the channel estimation at the receiver.

Taking into account these assumptions and parameters, a set of simulations was performed whose results are shown in Figure 3 for LTE downlink and in Figure 4 for LTE uplink. In both figures it can be observed that the maximum throughputs are not equal to the peak throughputs previously calculated. The reason is threefold: the used bandwidth is not 20 MHz but 10 MHz, the highest coding rate used is 0.93 instead of 1 and downlink control signals overhead is assumed to be 2 OFDM symbols instead of 1.

In LTE downlink, according to the results shown in Figure 3, MIMO 4×4 scheme provides a clearly better performance than the other schemes for almost all the useful SINR margin. Nevertheless, MIMO 2×2 scheme does not provide an important performance improvement until SINR reaches a value of 15 dB. Also, it can be observed that improvement factor in peak throughput due to MIMO schemes is far from being equal to the number of antennas (2 or 4). Instead, peak throughput is multiplied by 1.7 and 3.6 in MIMO 2×2 and MIMO 4×4 respectively. This is basically due to the higher quantity of reference signals needed in the MIMO schemes.

In LTE uplink, there is not any peak throughput gain when using more receiver antennas. But a nonnegligible SINR gain can be achieved. This gain is about 5 dB for a throughput of 20 Mbps. Note that in SIMO 1×4 maximum rate is achieved 10 dB before than in SIMO 1×2.

2.3.3. LTE System Level Performance. LTE performance analysis at system level requires the definition of system level statistics. The cell spectral efficiency and the cell edge user spectral efficiency are the more important ones. Given a multiuser/multicell scenario, the cell spectral efficiency is defined as the aggregate throughput of all users (the number of correctly received bits over a certain period of time) normalized by the overall cell bandwidth and divided by the number of cells. In the same scenario, the cell edge user spectral efficiency is the 5% point of CDF of the user throughput normalized with the overall cell bandwidth.

In order to calculate these values in the downlink, a dynamic system level simulator has been used. The main parameters of the considered scenario are shown in Table 1. The scenario is similar to the “Case 1” scenario in [9]. The main differences in this assessment are that the channel has been implemented using a tapped delay line model and a low correlation among channels has been assumed. Specifically, an ETU channel has been used [14]. The scheduler operation follows the proposal of [18] where scheduling algorithm is divided in two parts: one for the time domain and another for the frequency domain. For both domains a proportional fair approach has been used.

Following the proposed approach, average cell spectral efficiency in downlink was obtained yielding 1.52 bps/Hz/cell for SIMO 1×2, 1.70 bps/Hz/cell for MIMO 2×2 and 2.50 bps/Hz/cell for MIMO 4×4. The cell edge user spectral efficiencies are 0.02 bps/Hz/user, 0.03 bps/Hz/user and 0.05 bps/Hz/user, for the same antenna configurations. Note that the LTE values for the uplink have been extracted from the results presented by the 3GPP partners in [12], since the downlink values obtained in this assessment fit with 3GPP results. Since LTE requirements were defined as

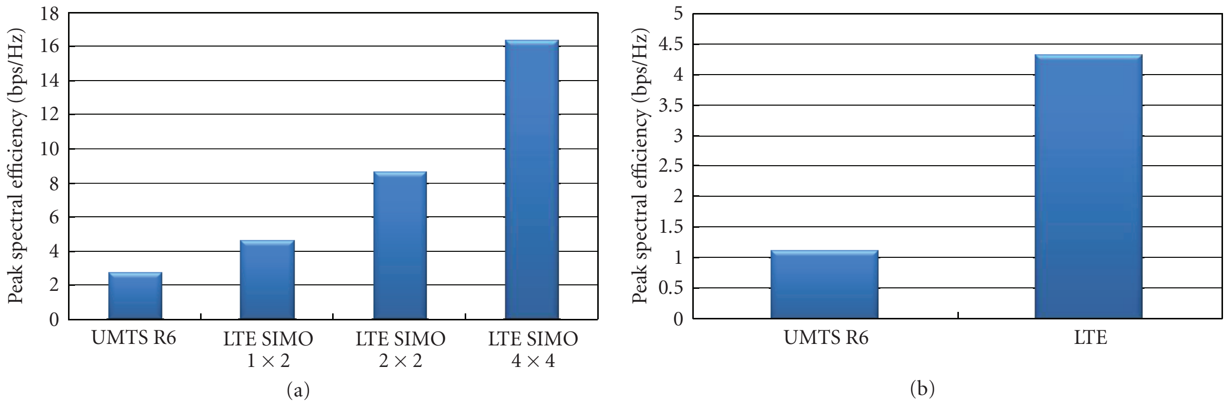

Figure 2: LTE peak spectral efficiencies in downlink (a) and uplink (b).

Table 1: Simulation parameters.

Common parameters		
Bandwidth		10 MHz (50 RB)
Channel		Tapped delay line: EPA with 5 Hz Doppler frequency at link level, ETU at system level
Central frequency		2.5 GHz
MCS		CQI 1–15
Multiantenna schemes	DL	SIMO 1 × 2, MIMO 2 × 2/4 × 4
	UL	SIMO 1 × 2/1 × 4
Control channels overhead	DL	2 OFDM symbols per subframe
	UL	Not considered
System level parameters		
Inter site distance (ISD)		500 m
Cell deployment		3-sector cells, reuse 1
Pathloss		130.2 + 37.6 log 10 (d(km)) dB
Shadowing		lognormal, $\sigma = 8$ dB
eNB transmission power		46 dBm
Noise spectral density		−174 dBm/Hz
Scheduler		Proportional Fair in time and frequency domains up to 5 UEs is scheduled per subframe
Mobility		Users moving at 30 km/h

relative to HSPA performance, Table 2 includes HSPA figures extracted also from [12, 13]. After direct inspection, it can be concluded that most of the requirements specified by 3GPP are fulfilled by the current Release 8 version of LTE.

3. LTE-Advanced and the Fourth-Generation Mobile

The process of defining the future IMT-Advanced family was started with a Circular Letter issued by ITU-R calling for submission of candidate Radio Interface Technologies (RITs) and fvcandidate sets of Radio Interface Technologies (SRITs) for IMT-Advanced [1]. However, all documents available in that moment concerning IMT-Advanced did not specify any new technical details about the properties of future 4G systems. Instead, they just reference the Recommendation M.1645 [19], in which the objectives of the future development of IMT-Advanced family were barely defined: to reach 100 Mb/s for mobile access and up to 1 Gb/s for nomadic wireless access. Unfortunately, it was not until November 2008 when the requirements related to technical performance for IMT-Advanced candidate radio interfaces were described [20].

Just after receiving the Circular Letter, the 3GPP organized a workshop on IMT-Advanced where the following decisions were made.

(i) LTE-Advanced will be an evolution of LTE. Therefore LTE-Advanced must be backward compatible with LTE Release 8.

(ii) LTE-Advanced requirements will meet or even exceed IMT-Advanced requirements following the ITU-R agenda.

(iii) LTE-Advanced should support significantly increased instantaneous peak data rates in order to reach ITU requirements. Primary focus should be on low mobility users. Moreover, it is required a further improvement of cell edge data rates.

Table 2: LTE requirements related to technical performance.

		Requirements LTE TR 25.913	LTE simulation results
Peak data rate (Gbps)		0.1	0.172 (2 × 2) 0.326 (4 × 4)
Latency		C-Plane < 100 ms U-Plane < 5 ms	—
Peak spectral efficiency (bps/Hz)	DL	5 (1 × 2)	4.56 (1 × 2) 8.64 (2 × 2) 16.32 (4 × 4)
	UL	2.5 (1 × 2)	4.32 (1 × 2)
Average spectral efficiency (bps/Hz/cell)	DL	EUTRA (2 × 2) 3-4 times HSDPA R6 {0.53}	1.52 (1 × 2) 1.70 (2 × 2) 2.50 (4 × 4)
	UL	EUTRA (1 × 2) 2-3 times HSUPA R6 (1 × 2) {0.332}	0.73 (1 × 2)
Cell edge user spectral efficiency (bps/Hz/cell/user)	DL	EUTRA (2 × 2) 2-3 times HSDPA R6 {0.02}	0.02 (1 × 2) 0.04 (2 × 2) 0.05 (4 × 4)
	UL	EUTRA (1 × 2) 2-3 times HSUPA R6 (1 × 2) {0.009}	0.02 (1 × 2)
Mobility		Up to 350 km/h	30 km/h
Bandwidth		Up to 20 MHz	10 MHz

Table 3: IMT-Advanced requirements related to LTE-Advanced requirements.

		Requirement ITU-R M.2134	Requirements LTE-A TR 36.913
Peak data rate (Gbps)		1	1-(DL) 0.5-(UL)
Latency		C-Plane < 100 ms U-Plane < 10 ms	C-Plane < 50 ms U-Plane < 5 ms
Peak spectral efficiency (bps/Hz)	DL	15 (4 × 4)	30 (8 × 8)
	UL	6.75 (2 × 4)	15 (4 × 4)
Cell spectral efficiency (bps/Hz/cell)	DL	2.2 (4 × 2)	2.4 (2 × 2) 2.6 (4 × 2) 3.7 (4 × 4)
	UL	1.4 (2 × 4)	1.2 (1 × 2) 2.0 (2 × 4)
Cell edge user spectral efficiency (bps/Hz/cell/user)	DL	0.06 (4 × 2)	0.07 (2 × 2) 0.09 (4 × 2) 0.12 (4 × 4)
	UL	0.03 (2 × 4)	0.04 (1 × 2) 0.07 (2 × 4)
Mobility		Up to 350 km/h	Up to 350 km/h
Bandwidth		>40 MHz	Up to 100 MHz

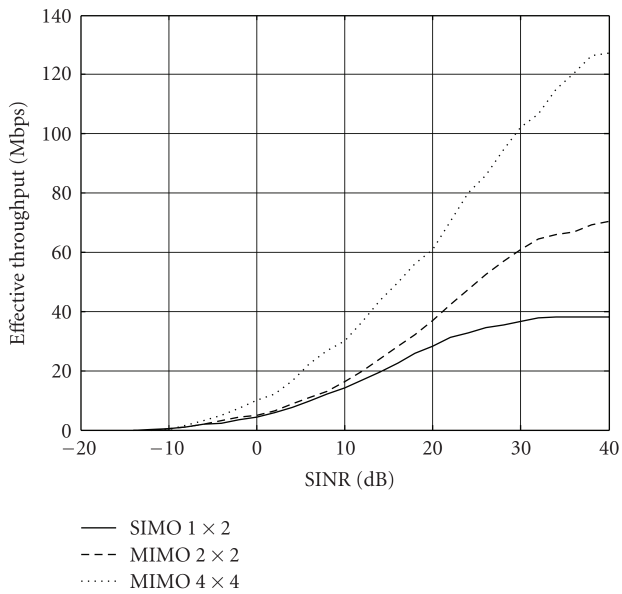

Figure 3: Link level evaluation of throughput versus SINR in LTE downlink.

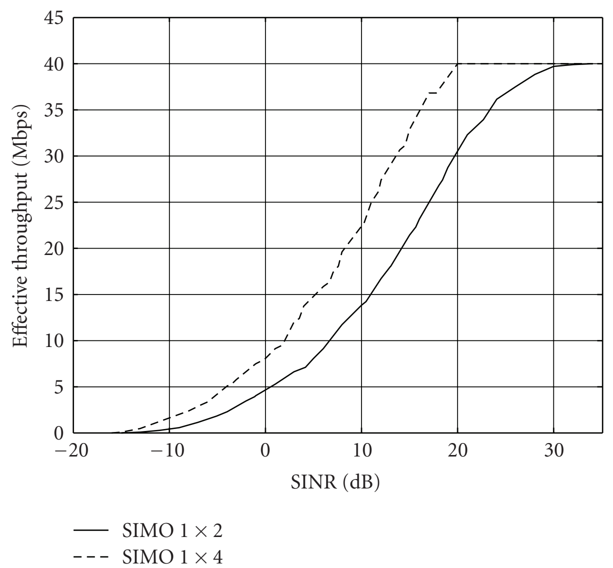

Figure 4: Link level evaluation of throughput versus SINR in LTE uplink.

With these clear objectives, and without knowing the final technical requirements yet, 3GPP defined a bullets list with the first requirements for LTE-Advanced and some technical proposals. Besides, it was decided to officially gather and approve them in the technical report TR 36.913 [21]. The remaining of this section deals with both aspects: requirements and technical proposals for LTE-Advanced.

3.1. LTE-Advanced Requirements. The requirement specification list was also included in TR 36.913. Although it is expected a list extension, these are some of the current agreements on the requirements for LTE-Advanced [21].

(i) Peak data rate of 1 Gbps for downlink (DL) and 500 Mbps for uplink (UL).

(ii) Regarding latency, in the C-plane the transition time from Idle to Connected should be lower than 50 ms. In the active state, a dormant user should take less than 10 ms to get synchronized and the scheduler should reduce the U-plane latency at maximum.

(iii) The system should support downlink peak spectral efficiency up to 30 bps/Hz and uplink peak spectral efficiency of 15 bps/Hz with an antenna configuration of 8×8 or less in DL and 4×4 or less in UL.

(iv) The 3GPP defined a base coverage urban scenario with intersite distance of 500 m and pedestrian users. Assuming this scenario, average user spectral efficiency in DL must be 2.4 bps/Hz/cell with MIMO 2×2, 2.6 bps/Hz/cell with MIMO 4×2 and 3.7 bps/Hz/cell with MIMO 4×4, whereas in UL the target average spectral efficiency is 1.2 bps/Hz/cell and 2.0 bps/Hz/cell with SIMO 1×2 and MIMO 2×4, respectively.

(v) In the same scenario with 10 users, cell edge user spectral efficiency will be 0.07 bps/Hz/cell/user in DL 2×2, 0.09 in DL 4×2 and 0.12 in DL 4×4. In the UL, this cell edge user spectral efficiency must be 0.04 bps/Hz/cell/user with SIMO 1×2 and 0.07 with MIMO 2×4.

(vi) The mobility and coverage requirements are identical to LTE Release 8. There are only differences with indoor deployments that need additional care in LTE-Advanced.

(vii) In terms of spectrum flexibility, the LTE-Advanced system will support scalable bandwidth and spectrum aggregation with transmission bandwidths up to 100 MHz in DL and UL.

(viii) LTE-Advanced must guarantee backward compatibility and interworking with LTE and with other 3GPP legacy systems.

Table 3 summarizes the list of requirements established by ITU-R and 3GPP allowing a direct comparison among 4G and LTE-Advanced. According to this table, it can be concluded that LTE-Advanced is being designed to be a strong candidate for next 4G, since it fulfils or even exceeds all IMT-Advanced requirements.

3.2. LTE-Advanced Technical Proposals. LTE Release 8 can already fulfill some of the requirements specified for IMT-Advanced systems. However, it is also clear that there are more challenging requirements under discussion in the 3GPP, which would need novel radio access techniques and system evolution. The 3GPP working groups, mainly RAN1 working on the physical layer, are currently evaluating some techniques to enhance LTE Release 8 performance. This section offers an overview of some of these proposals.

Support of Wider Bandwidth. A significant underlying feature of LTE-Advanced will be the flexible spectrum usage.

The framework for the LTE-Advanced air-interface technology is mostly determined by the use of wider bandwidths, potentially even up to 100 MHz, noncontiguous spectrum deployments, also referred to as spectrum aggregation, and a need for flexible spectrum usage.

In general OFDM provides a simple means to increase bandwidth: adding additional subcarriers. Due to the discontinuous spectrum reserved for IMT-Advanced, the available bandwidth might also be fragmented. Therefore, the user equipments should be able to filter, process and decode such a large variable bandwidth. The increased decoding complexity is one of the major challenges of this wider bandwidth.

Concerning the resource allocation in the eNB and the backward compatibility, minimum changes in the specifications will be required if scheduling, MIMO, Link Adaptation and HARQ are performed over groups of carriers of 20 MHz. For instance, a user receiving information in 100 MHz bandwidth will need 5 receiver chains, one per each 20 MHz block.

Coordinated Multiple Point Transmission and Reception. Coordinated multi point transmission and reception are considered for LTE-Advanced as one of the most promising techniques to improve data rates, hence increasing average cell throughput. It consists in coordinating the transmission and reception of signal from/to one UE in several geographically distributed points. So far, the discussions have focused on classifying the different alternatives and identifying their constraints. Potential impact on specifications comprises three areas: feedback and measurement mechanisms from the UE, preprocessing schemes and reference signal design.

Relaying Functionality. Relaying can be afforded from three different levels of complexity. The simplest one is the Layer 1 relaying, that is, the usage of repeaters. Repeaters receive the signal, amplify it and retransmit the information thus covering black holes inside cells. Terminals can make use of the repeated and direct signals. However, in order to combine constructively both signals there should be a small delay, less than the cyclic prefix, in their reception.

In Layer 2 relaying the relay node has the capability of controlling at least part of the RRM functionality. In some slots the relay node acts as a user terminal being in the subsequent slot a base station transmitting to some users located close to the relay.

Finally, Layer 3 relaying is conceived to use the LTE radio access in the backhaul wireless connecting one eNB with another eNB that behaves as a central hub. This anchor eNB routes the packets between the wired and wireless backhaul, acting like an IP router.

Enhanced Multiple-Input Multiple-Output Transmission. Another significant element of the LTE-Advanced technology framework is MIMO, as in theory it offers a simple way to increase the spectral efficiency. The combination of higher order MIMO transmission, beamforming or MultiUser (MU) MIMO is envisaged as one of the key technologies for LTE-Advanced.

In case of spectrum aggregation, the antenna correlation may be different in each spectrum segment given a fixed antenna configuration. Therefore, in LTE-Advanced one channel element may encompass both low correlation and high correlation scenarios simultaneously. Since MU-MIMO is more appropriated for high correlation scenarios than Single-User (SU) MIMO, to fully utilize the characteristics of different scattering scenarios both SU-MIMO and MU-MIMO should be simultaneously used.

4. Conclusions

LTE has been designed as a future technology to cope with next user requirements. In this paper two complete LTE Release 8 link and system level simulators have been presented together with several performance results. Based on these results, this paper concludes that LTE will offer peak rates of more than 150 Mbps in the downlink and 40 Mbps in the uplink with 10 MHz bandwidth. Besides, in the downlink the minimum average throughput will be around 30 Mbps, which represents a quite significant improvement in the cellular systems performance. As compared with current cellular systems, LTE entails an enhancement of more than six times the performance of HSDPA/HSUPA.

This paper has also given an initial insight into the new technical proposals currently under discussion in the framework of 3GPP. This analysis allows those who are interested in wireless communications to get aligned with the research community towards the definition and optimization of next Fourth-Generation mobile.

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