Evaluation of 3GPP Technology Candidate Towards Fourth Generation Mobile

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Resumen — LTE-Advanced es una de las tecnologías candidatas para convertirse en la próxima generación de comunicaciones móviles (4G). Es responsabilidad de la Unión Internacional de las Telecomunicaciones (UIT) evaluar esta tecnología a través de los Grupos de Evaluación Externos (GEE), entre los cuales se encuentra el consorcio WINNER+ (*Wireless World Initiative New Radio +*). El Grupo de Comunicaciones Móviles (GCM) del Instituto de Telecomunicaciones y Aplicaciones Multimedia, como socio de WINNER+, está analizando diferentes técnicas para optimizar la red de acceso radio LTE-Advanced. Esta tesina de máster se enmarca dentro de este trabajo, y especialmente, en la comparación de los turbo-códigos (TC) y *Low Density Partity Check* (LDPC) para anchos de banda de hasta 100 MHz. Los resultados obtenidos muestran que tanto los TC como los LDPC son buenos codificadores para esos tamaños de bloque. Los códigos LDPC representan una mejora de 0.5 dB como máximo respecto a los TC. Además, se ha realizado un estudio de prestaciones de la capa física de LTE en el enlace ascendente y descendente, junto con una propuesta de calibración de este tipo de simulaciones de enlace.

Abstract — LTE-Advanced is one promising candidate technology to become part of the next generation mobile (4G). It is up to the International Telecommunication Union (ITU) standardization body to assess this technology through the External Evaluation Groups (EEG), being one of them the WINNER+ project (Wireless World Initiative New Radio +). The Mobile Communications Group (MCG) of the Institute of Telecommunications and Multimedia Applications, as a partner of WINNER+, is currently analyzing and proposing different techniques with the aim of optimizing the LTE-Advanced radio access network. This Master Thesis is part of this activity and, especially, on the comparison of Turbo (TC) and Low Density Parity Check (LDPC) codes for bandwidths up to 100 MHz. Results prove that both TC and LDPC codes are good encoders for those block sizes. The LDPC codes only entail a maximum 0.5 dB improvement as compared with TC. In addition to this assessment, a performance study of LTE downlink/uplink (DL/ UL) physical layer together with a calibration proposal for link level simulations has been carried out.

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I INTRODUCTION

I.1 BACKGROUND

Social and economical aspects control the development of the mobile communications business. Consumer demand boosts all the technological advances, operators' capital investments and the amendment of the laws required to ensure the advance of the knowledge society towards the improvement of the quality of life of the citizens.

The mobile communications sector is characterized by a worldwide rapid increase in the number of users. According to the International Telecommunication Union (ITU), in the last five years the number of worldwide subscribers has grown from 1.2 billion to more than 3.3 billion (49.42% of the world population), which implies growing at a Compound Annual Growth Rate (CAGR) of 23.3%. Even though these numbers are quite significant, it is worth noting that, in terms of the number of subscribers, the mobile communications sector has reached saturation point in a wide number of markets. In the European Union, mobile penetration rate is over 110%, whereas in developed Asian countries has reached 80%, just like in United States and Eastern Europe where the growth of mobile services has been quite important in the last years. Although there is still room for the potential mid-term growth of less-developed markets, operators in saturated markets need to foster the demand of new services to guarantee the future increase in their revenues. Consequently, in the years to come the mobile communications sector will be forced to increase Average Revenue Per User (ARPU) levels.

That is why the scope of the mobile communications sector, also stated by ITU, is today more than ever to put on the market a new set of telecommunication services through the mobile phones. Among these services mobile TV, video on demand, interactive games and high quality music are expected to ensure a sharp upturn in usage of mobile services and consequent revenues.

With the aim of identifying the regulatory requirements of the sector, both the European Union and the UMTS Forum ordered market studies to foresee the future service demand and the traffic generated by this new demand. These studies are Future Mobile Services [1] and Magic Mobile Future 2010-2020 [2] respectively, whose market projections were based on the popularization of the abovementioned services and in the current upward trend of the market. Both studies predict a great rising in the traffic generated by mobile users until 2020, being the current mobile communication systems incapable of managing such increase.

Long Term Evolution (LTE) is the name given to the new standard developed by 3rd Generation Partnership Project (3GPP) to cope with these future market requirements. Therefore, LTE is the next step in the evolution of 2G and 3G systems and also in the provisioning of levels of quality similar to those of current wired networks. Due to the advantages offered by the Orthogonal Frequency Division Multiplexing (OFDM) technique, LTE can offer higher spectral efficiency than previous 3GPP technologies. This great improvement of throughput will likely transform the mobile business model and the mobile user behavior.

LTE can be deployed in scalable bandwidths ranging from 1.25 MHz up to 20 MHz and in all frequency bands designated by ITU for International Mobile Telecommunications (IMT). This feature and the system performance targets defined by the standard give operators considerable flexibility in their future technical and business strategies. Moreover, the capability of changing the working bandwidth of LTE allows operators to deploy this technology in any of their already-available frequency bands. This migration of less efficient technologies to LTE, also referred to as re-farming, will permit addressing future traffic demands. This fact is drawing the attention of not only those operators following the 3GPP specifications but also of other operators that have already expressed their interest in LTE as an evolutionary good option to reduce their expenditures thanks to the economies of scale.

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. This system is called LTE-Advanced and it supposes a forward step towards the next mobile communications network. The 3GPP working groups, mainly RAN1 working on the physical layer, are currently evaluating some techniques to enhance LTE Release 8 performance. The enhancements suggested for 3GPP are: support of wider bandwidth, coordinated multiple point transmission and reception, relaying functionality and enhanced multiple-input multiple-output transmission. The first item will be studied in detail in the section III.3, whereas the rest of topics will be explained in the following lines.

Coordinated multi point transmission and reception is considered for LTE-Advanced as one of the most promising techniques to improve the coverage of high data rates, hence increasing average cell throughput. It consists in coordinating the transmission and reception of signal from/to one user equipment (UE) in several geographically distributed points. So far, the discussions have focused on classifying the different alternatives and identifying their constraints.

Relaying can be afforded from three different levels of complexity. The simplest one is the Layer 1 relaying, i.e. 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 Radio Resource Management (RRM) functionality. In some slots the relay node acts as a UE 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 E-Node B with another E-Node B that behaves as a central hub. This anchor E-Node B routes the packets between the wired and wireless backhaul, acting like an IP router.

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

On the other hand, Worldwide Interoperability for Microwave Access (WiMAX) in its version 802.16m (mobile) is another technology going to compete with LTE-Advanced for the mobile communication market in the next years. IEEE 802.16m uses OFDMA as multiple access scheme in downlink (DL) and uplink (UL), unlike LTE which only use OFDMA in DL. On the other hand, incremental redundancy is used to determine the selection of bits to be retransmitted in the Hybrid Automatic Repeat Request (HARQ) process. Finally, it is worth noting that both, convolutional turbo codes, are supported. It is not yet clear if LDPC will be added to the final candidate proposal and strong discussions are ongoing in the framework of the IEEE. For general information about WiMAX 802.16m, reader can consult [3], or more specially, the IEEE 802.16 standard [4].

Therefore, a priori, there are two candidate technologies to be submitted to the ITU for their evaluation. Since ITU is not a technical organization, it has appointed a set of different investigation groups and international organisms that are going to act as External Evaluation Groups (EEGs). The project Wireless World Initiative New Radio+ (WINNER+) [5] is one of the twelve EEGs that will submit evaluation reports about the proposed Radio Interface Technologies (RITs). WINNER+ is a consortium of 29 partners coordinated by Nokia Siemens Networks and whose main objective is to develop, optimize and evaluate IMT-Advanced technologies. Moreover, WINNER+ is devising new technological proposals which can be included in future standards. The Institute of Telecommunications and Multimedia Applications

(iTEAM) of the Universidad Politécnica de Valencia is the only Spanish member of WINNER+, what permits iTEAM to know technology details in advance and also to introduce improvements in the specifications.

In order to be able to assess and make new contributions to LTE-Advanced standard, first it is necessary to develop a software tool simulating the transmission between a Base Station (BS) and a User Equipment (UE) in DL and UL. All physical and link layer protocols must be implemented in detail. This work has been carried out in two phases. In the first one, during the author's Final Project Work, an LTE Release 8 fully-compliant simulation tool was implemented in DL. This tool was validated against 3GPP simulations but assuming only Single Input Single Output because up to that date, 3GPP had not yet validated MIMO. The current Master Thesis work started at this point of development of the simulation tool, with the main objective of ending up LTE assessment, MIMO and UL included, and incorporating some of the new LTE-Advanced characteristics, specifically channel modeling and carrier aggregation. It must be noted that nowadays LTE-Advanced simulator does not incorporate coordinated multipoint, relaying and MIMO 8x8, leaving these tasks for further work in author's Thesis.

I.2   STATE OF THE ART

LTE is the previous step to the LTE-Advanced technology proposed by 3GPP. The LTE physical layer was totally standardized in December 2008 ([6] and [7]): physical channels, modulation, multiplexing and channel coding. The most important aspects are going to be analyzed in the next paragraphs.

One of the objectives marked by ITU is high data rate. However, it causes the symbol period being much smaller than the channel delay spread. This generates Inter-symbol Interference (ISI). In OFDM, the data stream is firstly serial-to-parallel converted to modulate onto M parallel subcarriers. This increases the symbol duration on each subcarrier by a factor of M in such a way that it becomes longer than the channel delay spread. A good summary of the main aspects of OFDM modulation is presented in [8].

When it is not possible to augment the available bandwidth, the increase in number of transmitter and receiver antennas is a good way to increase the transmitted throughput. In LTE, the maximum configuration is spatial multiplexing with four antennas in transmission and four antennas in reception. In LTE-Advanced, this number reaches eight antennas in transmission and reception. Different processing schemes of the broadband signal are showed in [8] or [9].

The channel estimation is another of the important aspects that configures the receiver efficiency. Most authors simulate the processing chain through ideal channel estimation.

However, this is an optimist assumption that does not reflect the real situation in a mobile communications system. For instance, the errors in the estimation will affect the reception of the symbols. Therefore, it is important to implement realistic estimation methods. In [10], [11], [12] and [13], channel estimation algorithms for OFDM systems are discussed.

All these aspects are equally valid for the 4G technologies. Within this framework, LTE-Advanced proposes a series of mechanisms to reach the demanding requirements defined by ITU [14]. The further advancements for the Evolved UMTS Terrestrial Radio Access Advanced (E-UTRA) are presented in [15]. An overview of some technology components of LTE-Advanced is provided in [16]. The carrier aggregation is one of the main factors of the success of the next 4G technologies. This concept implies transmitting data on multiple contiguous or non-contiguous sub-bands, called component carriers. Each component carrier occupies up to 20 MHz of bandwidth in which it can be transmitted information towards LTE or LTE-Advanced mobiles. Therefore, both LTE and LTE-Advanced systems are intended to coexist in the same frequency bands. In the same way, there will be exclusive bands for LTE-Advanced. As a consequence of that, a terminal may simultaneously receive one or multiple component carriers depending on its capabilities. These concepts are explained in the technical report [15].

In case of larger bandwidths then transmission capability increases. However, when a UE receives data from several frequency bands it is not still clear the best choice, whether to encode data in separate transport blocks or to combine all information and distribute the bits in the physical layer. Besides, comparing LDPC and turbo codes, the former tends to behave better with longer blocks and hence it could be reasonable to change the channel coding mechanism. Indeed, during the study phase of LTE, the operators and manufacturers discussed about this alternative. In [17] and [18], a performance study is realized, comparing the complexity of both schemes. The final decision was not technical but rather turbo codes were kept in order to have a technology in the market as soon as possible.

WiMAX is for sure the other main technology that is going to compete with LTE-Advanced for the mobile telecommunication market. WiMAX in its version 802.16e (current mobile WiMAX) uses LDPC, but in its version 802.16m [19], up to now the selected coder is turbo codes and LDPC is left for further study. The IEEE has also carried out similar studies as the ones from 3GPP, like [20] or [21].

With the aim of evaluating some proposed IMT-Advanced radio interface technologies, it is necessary to establish both an evaluation procedure and criteria. The evaluation procedures are based on simulation (link and system level), inspection or analytical methods. Moreover, accurate channel models are needed in the evaluations of the IMT-Advanced candidate RITs to emulate realistic propagation conditions. Hence, multi-link models with geometry-based

stochastic channel models have been proposed by the ITU-R. The IMT-Advanced channel model (generic model) consists of a Primary Module and an Extension Module. The first module is based on the WINNER II channel model [22]. A reduced variability model with fixed parameters is called cluster delay line which is an extension of the tap delay line model. This model is more inexact than the generic model but it can be used for calibration purposes. The description of the generic model and the cluster delay line model can be found in [23].

I.3   OBJECTIVES

In the modern communication systems, before proceeding with the physical implementation it is necessary to perform a software characterisation. In this system simulation all type of imperfections existing in the real world must be modelled to be able to measure system performance and introduce corrections with the objective of being more efficient.

The simultaneous software simulation of all elements (BS and UE) and processes (modulation, codification, multiplexation, scheduling, admission control, etc) of a wireless communication is unfeasible from a point of view of computational complexity. Hence, the simulations are divided in two abstractions levels: link and system level simulation. In link level simulations, the scope of this Master Thesis, the transmission between one UE and one BS is emulated including the following processes: codification, modulation, signal generation, channel modelling, equalization, demodulation and decodification.

As abovementioned, the first phase of the work towards LTE-Advanced link level evaluation consisted in implementing the simulator according to LTE Release 8 specifications. This work was completed along the author's Final Project Work. When the LTE simulator was finished and validated the objectives of the current dissertation were defined:

- To design the new structure of the LTE simulator and the new programming objects according to the last changes which took place in the specifications.

- To introduce the processing chain in the receiver to be able to recover the signal with antenna configurations of up to four antennas in transmission and four antennas in reception (MIMO).

- To implement the UL LTE simulator according to the specifications and thanks to the experience of the DL LTE simulator.

- To establish a calibration procedure for the LTE link level simulations.

- To complete a full assessment of LTE Release 8 standard.

- To implement the IMT-Advanced channel model according to ITU report M.2135 [23].

- To adapt LTE simulator to process LTE-Advanced signals in different frequency bands.

- To study the performance of LDPC codes with respect to turbo codes in different frequency bands and variable bandwidths.

I.4 RELEVANCE Y APLICABILITY OF THE DISSERTATION

The WINNER+ project is not intended to write down a proposal for IMT-Advanced as 3GPP or IEEE did. However, WINNER+ system concept represents a reference design that may be taken up by other standardization organisms interested in it. The starting point for the WINNER+ project is 3GPP LTE, with additional innovative features from WINNER-II, the legacy project before WINNER+. In Fig. 1, the timeline of 3GPP standardization from the origin until LTE deployment is depicted. In this process, the WINNER+ project is developing different reports about some aspects related to the radio access network. Each organism belonging to WINNER+ studies a different topic. For instance, the iTEAM committed to elaborates a report to WINNER+ about the advantages and disadvantages of using LDPC codes for block sizes filling a bandwidth of up to 100 MHz without dividing the transport block in smaller blocks. Hence, this Master Thesis is absolutely aligned with this research line.

Moreover, the development of link level simulation tools allows the author to investigate about the performance of 3GPP technology towards IMT-Advanced. For instance, a performance evaluation of LTE, considering a transmission chain fully compliant with LTE Release 8 and including realistic HARQ and turbo-decoding, was accepted for publication in the EURASIP Journal on Wireless Communications and Networking [24], listed in the second third of the Journal Citation Report. The LTE capacity was 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.

Another of the main outcomes of this dissertation was the evaluation of different channel estimators for LTE, work presented in the IEEE Vehicular Technology Conference [25]. Results compared the difference among them, checking the robustness of the estimators against errors. Besides, this paper performed a LTE system performance assessment employing a realistic channel estimator.
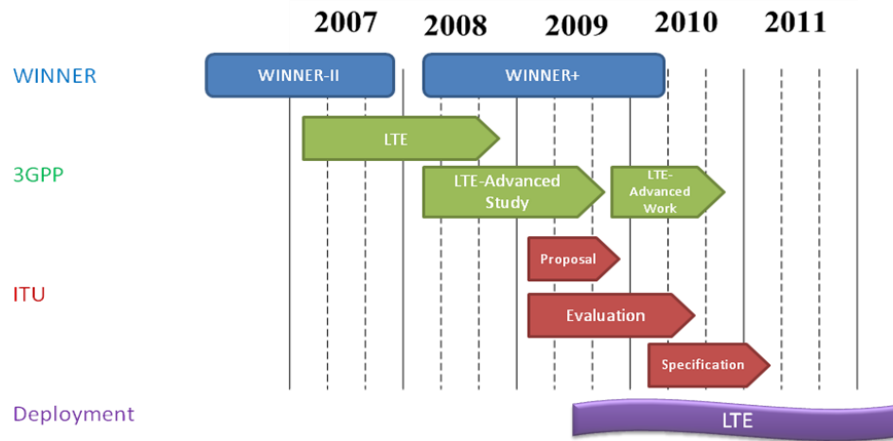
Fig. 1 Evolution of the tasks of WINNER, ITU and 3GPP

Some of the studied methods assume that channel statistics are known 'a priori'. Those methods performing Wiener filtering in frequency domain assume a perfect knowledge of the frequency domain correlation (or equivalently, of the channel Power Delay Profile, PDP) and the noise power (or equivalently, of the Signal to Noise Ratio, SNR), whereas those methods performing Wiener filtering in time domain assume the knowledge of the time domain correlation of the channel (or equivalently, of the Doppler frequency). Unfortunately, information about the channel statistics is not available at the receiver, although it can be estimated. Therefore, the objective of this paper was to evaluate the errors in the estimation of these parameters and propose an estimator with a complexity and memory requirements are reduced. This estimator realizes a Wiener filtering in frequency thanks to six nearest symbols pilots and a linear interpolation in the time domain.

With the acquired experience developing a LTE DL/UL simulator and in order to fill the link level calibration gap, an internal activity for the definition of an accurate harmonisation procedure was performed within WINNER+, being submitted for evaluation in another high quality journal [26]. The intention of this action was to share the experience, information and benchmark data with the remaining EEGs in order to foster the required coordination and unification of results.

The scope of the activity and the corresponding paper was to present the complete link level calibration process methodology defined in the framework of WINNER+, starting from the OFDM testing up to the link-to-system modelling. Since 3GPP LTE is precursory of LTE-Advanced, this paper focused on the LTE technology. Besides, the resulting process of calibration described in the paper was partially based on the experience of evaluation of LTE performance inside the 3GPP, and is totally aligned with their conclusion, which validates the overall process.

Finally it is work highlighting that several papers deal with the performance evaluation of LTE in FDD mode. However, up to date this assessment has been done partially because of the following reasons. First, some of these works only focused on the physical layer, leaving out the retransmission processes and error correction. System level analysis need MAC layer performance information and cannot be carried out with only a physical layer characterization. Second, other papers assess the performance of LTE radio access network assumed ideal channel estimation, which results in an optimistic estimation of LTE capacity. Finally, other works including the complete transmission chain assume an interference free environment and do not provide the information required by system level simulators. Therefore, this Master Thesis presents a method to evaluate LTE radio performance considering a transmission chain fully compliant with LTE Release 8 and including realistic HARQ (Hybrid ARQ) and turbo-decoding.

Thanks to this work, iTEAM owes one complete simulation tool, only comparable with the simulation capabilities of Nokia Siemens Networks (NSN) and Ericsson. In fact, in the last days before the writing of this document, iTEAM is involved in the calibration process of LTE simulation tools in WINNER+, in which only iTEAM, NSN and Ericsson are involved. This gives some light of the relevance of this Master Thesis for the positioning of the Universidad Politécnica de Valencia in next generation mobile technologies.

I.5   STRUCTURE OF THE MASTER THESIS

This dissertation evaluates the 3GPP technology as candidate to be the fourth generation mobile. The rest of the dissertation is organized as follows:

- In Section II, the most important concepts of the LTE physical layer will be presented. Immediately afterwards, a calibration procedure for link level simulations is presented. Finally, an evaluation of the performance of LTE is exposed.
- In Section III, the evolution of the LTE simulation tool towards LTE-Advanced is examined. The most relevant changes required in the simulator are investigated: the IMT-Advanced channel and carrier aggregation. Besides, LDPC codes are presented as an alternative for further improvement of IMT-Advanced systems.
- In Section IV, LDPC codes are validated inside the LTE-Advanced simulator. Afterwards, a comparison between LDPC and turbo codes is analyzed for different block sizes. Moreover, some of the most important parameters of the LDPC codes are examined, for instance, the type of decoding algorithm and the number of iterations.
- Finally, the conclusions of the investigation as well as the future research lines are presented in Section V.

II   LONG TERM EVOLUTION

II.1   *SOME DETAILS ON THE LTE LINK LEVEL SIMULATOR*

As abovementioned, a LTE link level simulator must cover all relevant aspects of the technology, i.e. codification, modulation, signal generation, etc. All these aspects belong to the transmission stage which is standardized in the specifications [6] and [7]. The receiver chain will realize all necessary tasks to decode and process the broadband signal. The most important aspects in the LTE system characterization are depicted in Fig. 2.

Due to the channel variability and multipath effect is necessary to estimate the channel by means of reference signals. In the simulator, several realistic estimators have been implemented. It allows simulating the waste of performance that a real mobile would support due to channel estimation. Normally, in most of papers, the authors measure the performance (BLER, Throughput, etc) with ideal channel estimation. However, this supposes an overestimation of the realistic performance of the system.

For the channel coding a turbo encoder with rate 1/3 is used. The scheme of the turbo encoder is a parallel concatenated convolutional code (PCCC) with two recursive systematic convolutional coders (RSCs) and one turbo code internal interleaver. Afterwards, each stream (systematic bits and two streams of parity bits) is joined in a soft buffer in which the bits are selected to achieve the desired rate through a rate matching stage.

In order to study the performance of any technology it is necessary to include in the simulator a realistic channel model. The first implemented channel, extracted from 3GPP, is valid for a bandwidth of up to 20 MHz using the classical scheme with tap delay line. Concerning the simulation of Rayleigh fading sequences, two main approaches have been implemented: a filtering method and sum of sinusoids method. After the publication of ITU-R reference scenarios, the new stochastic geographic channel model was included in the link level simulator, using only the small scale parameters.

One data channel in LTE corresponds to one resource element, which encompasses a bandwidth of 15 kHz and an OFDM symbol. Precisely, the ODFM transmission is a very good technique to modulate signals in frequency and time. Thanks to the division of time and spectrum, it is possible to structure the spectrum to assign resources to different users in an optimum way. This technique is very useful to combat the frequency selectivity since if there is strong fading in any frequency only a few symbols will be affected.
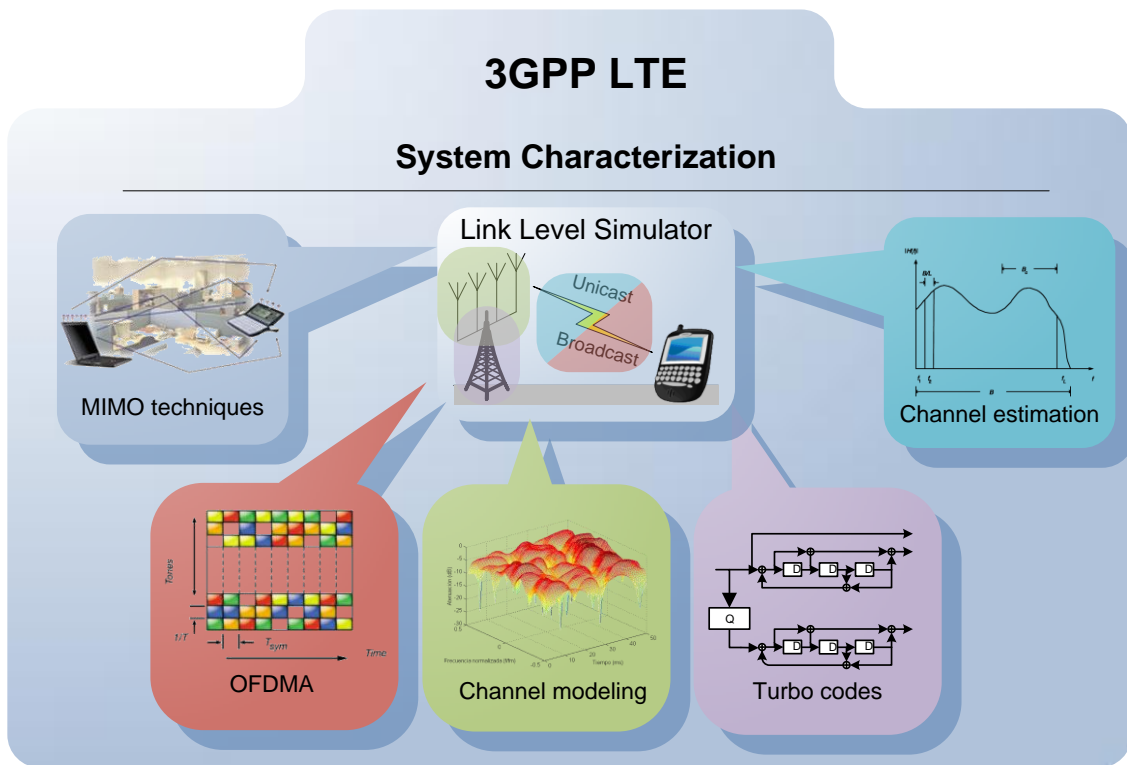
Fig. 2 LTE System characterization

One of the keys of success of LTE is the use of multiple antennas in transmission and reception (MIMO), what increases the transmitted throughput. The antenna configurations in LTE are: single antenna, single input multiple output, transmit diversity and spatial multiplexing.

The transmission of packets is subject to errors due to the variations of the channel quality. These errors provoke that the packet must be retransmitted. In LTE, the technique used is called Automatic Repeat Request (ARQ) with soft combining. In an ARQ scheme, the receiver uses an errors detection code, called Cyclic Redundancy Check (CRC), to detect any erroneous packet. If there is not any error in the received packet, a positive Acknowledgment (ACK) is sent, otherwise transmitting a Negative Acknowledgment (NACK). This scheme together with turbo codes constitutes the technique referred to as Hybrid ARQ (HARQ). The HARQ retransmission must, by definition, contain the same quantity of information bits than the original transmission. However, the quantity of coded bits can be chosen in a different way. Incremental redundancy is the soft combining method implemented in LTE. It consist in retransmitting different bits respects to first transmission.

II.2   *CALIBRATION PROPOSAL*

Taking advantage of the experience acquired after implementing three different simulators, (LTE DL/UL and LTE-Advanced) and in collaboration with other WINNER+ partners, it has been proposed a calibration procedure for IMT-Advanced link level simulations [26].

This section summarizes the complete link level calibration process methodology defined in the framework of WINNER+, focussing on the key aspects of the LTE system and starting from the OFDM testing up to the link-to-system interface model verification. A detailed step-wise approach able to execute the calibration process for the link level simulator has been provided in the Fig. 3. The methodology is based on breaking down the entire simulation chain into its single building blocks, identifying basic subsets of functionalities.
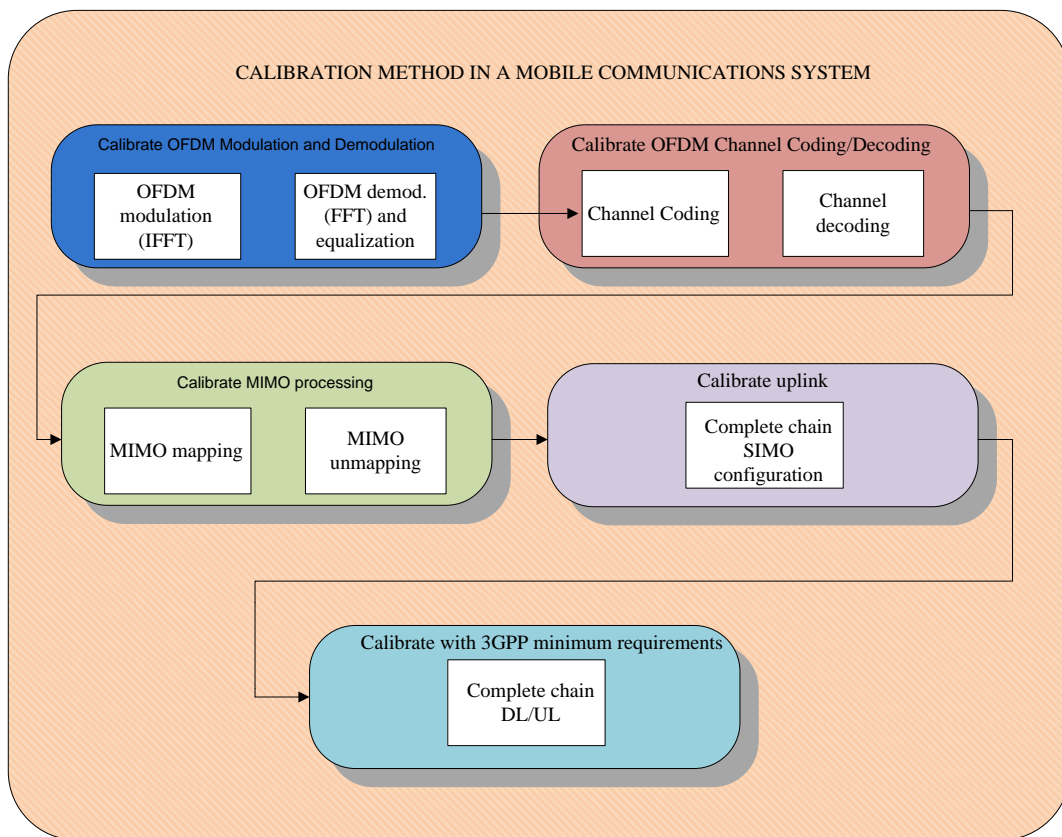

Fig. 3 Link Level calibration process

The first phase of the calibration process is to verify the correctness of each single functional block within the simulation chain. Afterwards, the entire simulation chain is aligned to a valid reference for the particular system under consideration. A possible procedure for this task can be based on the direct comparison of the E2E link level simulation results with other outcomes provided by the research community, when referring to common simulation scenarios. In particular, when presenting the LTE link level calibration methodology, we have provided in

[26] a significant set of references from 3GPP documentation, strengthening and validating the overall process.

The OFDM modulation can be validated through the theoretic curves both AWGN and multipath channel [27]. The channel coding is not possible to evaluate through theoretic curves and for this reason it must be evaluated with results of other companies. For instance, an AWGN channel without retransmissions and a Zero Forcing receiver is simulated in [28]. On the other hand, multi-antenna configurations (SIMO and MIMO) can be analysed with minimum requirements stated by 3GPP [29]. The minimum requirements for the reverse channel are listed in [30].

This study may represent a valuable guide for link level simulator calibration in the forthcoming EEG simulation phase, within the performance evaluation process of IMT-Advanced technology proposals, guaranteeing, when it is followed, complete consistency and comparability of the obtained results.

II.3   LTE PERFORMANCE EVALUATION

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 or inspections methods are valid to evaluate peak data rates or peak spectral efficiencies. However, a deeper performance analysis requires the usage of simulation.

The peak spectral efficiency is the highest theoretical data rate assignable to a single mobile user divided by the allocated bandwidth. 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 20MHz the maximum achievable rates in downlink are: 91.2 Mbps for SIMO 1x2, 172.8 Mbps for MIMO 2x2 and 326.4 Mbps for MIMO 4x4. The resulting peak spectral efficiencies are 4.56, 8.64 and 16.32 b/s/Hz for the considered multi-antenna schemes. In uplink with SIMO 1x2 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.

The calculated peak spectral efficiencies of LTE are depicted in Fig. 4 for both downlink and uplink together with the efficiencies of UMTS Release 6, i.e. including HSDPA and HSUPA. From this peak spectrum efficiency it can be seen that LTE with 20MHz meets and exceeds the 100Mbps downlink and 50Mbps 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.

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.
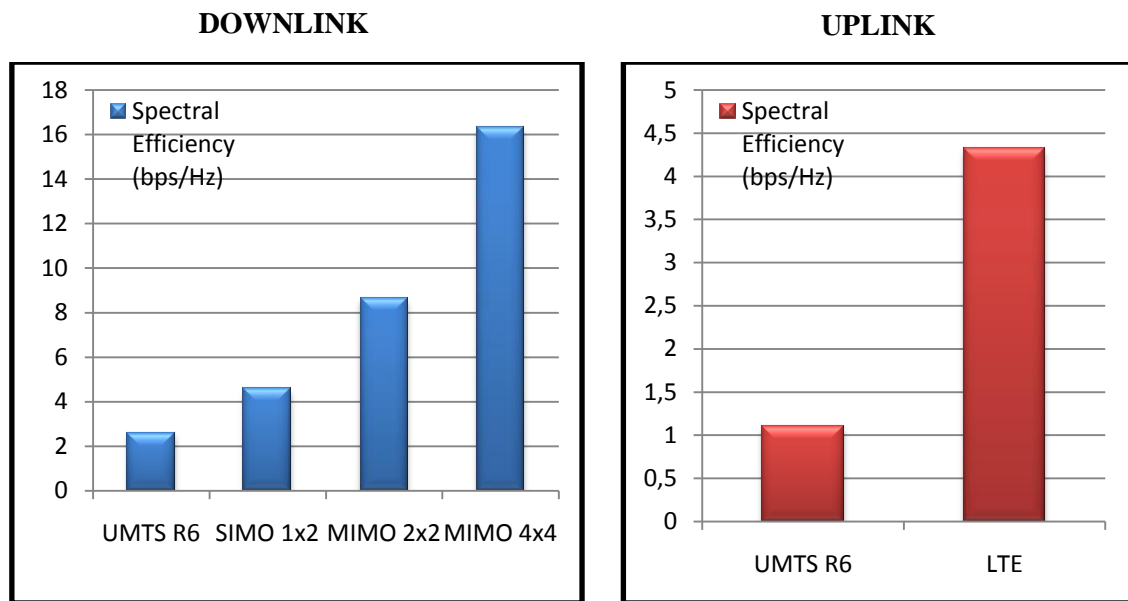
DOWNLINK   **UPLINK**

Fig. 4 LTE Spectral efficiency in downlink (left) and uplink (right)

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 [29] with a Doppler frequency of 5Hz. The central frequency was set to 2.5GHz, the most likely band for initial LTE deployment. A set of modulation and coding schemes was selected from the CQI table included in LTE specifications [31]. This set was defined 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 multi-antenna 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.

Parameter	Value
Bandwidth	10 MHz (50RB)
Channel model	EPA model, 5 Hz Doppler frequency
Central frequency	2.5 GHz
MCS	CQI 4-15
Multi-antenna schemes	DL: SIMO 1x2, MIMO 2x2/ 4x4 UL: SIMO 1x2/ 1x4
Control channels	2 OFDM symbols per subframe Not considered

Table 1 Simulation parameters to evaluate the LTE performance.

Concerning LTE downlink, different multi-antenna configurations were modeled including SIMO 1x2, MIMO 2x2 and MIMO 4x4. Simulated MIMO scheme followed the open loop spatial multiplexing scheme as specified by the 3GPP [6], the number of codewords were 2 and the number of layers was equal to the number of transmit antennas, i.e. 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 were considered.

In the uplink, two different multi-antenna configurations were simulated: SIMO 1x2 and SIMO 1x4. 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 [7], 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 Fig. 5 for LTE downlink and in Fig. 6 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 that both in downlink and uplink, the highest coding rate used is not 1 but around 0.96. Besides, in downlink control channels overhead reduces the maximum achievable data rate, which was not considered in the peak spectral efficiency calculation due to its definition.

In LTE downlink, according to the results shown in Fig. 5, MIMO 4x4 scheme provides a clearly better performance than the other schemes for almost all the useful SINR margin. Nevertheless, MIMO 2x2 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 2 or 4. Instead, throughput is multiplied by 1.7 and 3.6 in MIMO 2x2 and MIMO 4x4 respectively. This is basically due to the higher quantity of reference signals needed in the MIMO schemes.

In LTE uplink, there is not any throughput gain when using more receiver antennas. But a non-negligible SINR gain can be achieved. This gain is about 5 dB for a throughput of 20 Mbps (see Fig. 6). Note that in SIMO 1x4 maximum rate is achieved 10 dB before than in SIMO 1x2.
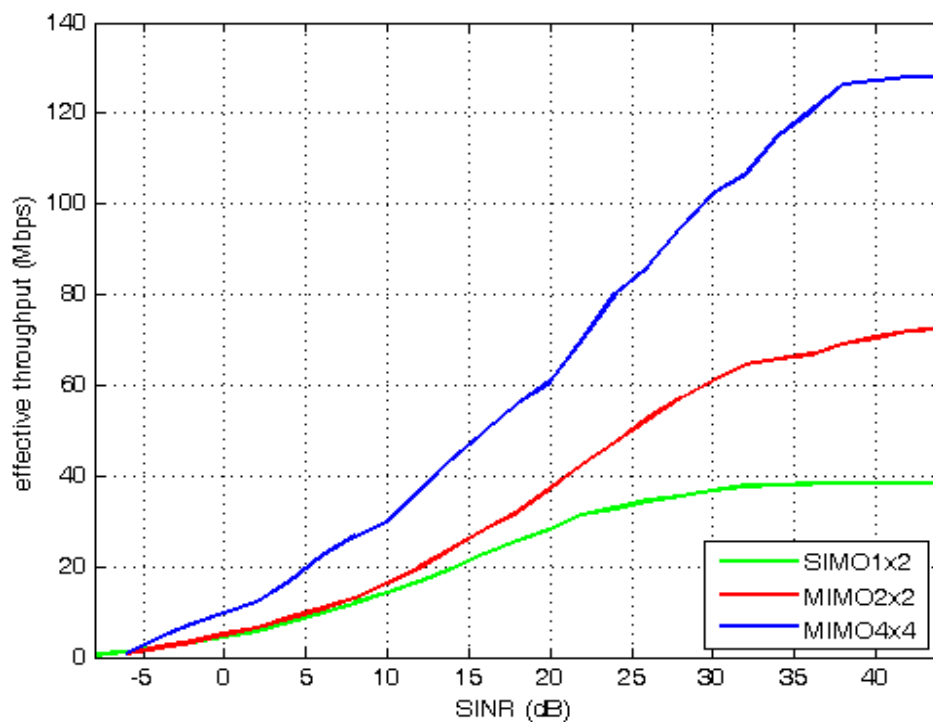

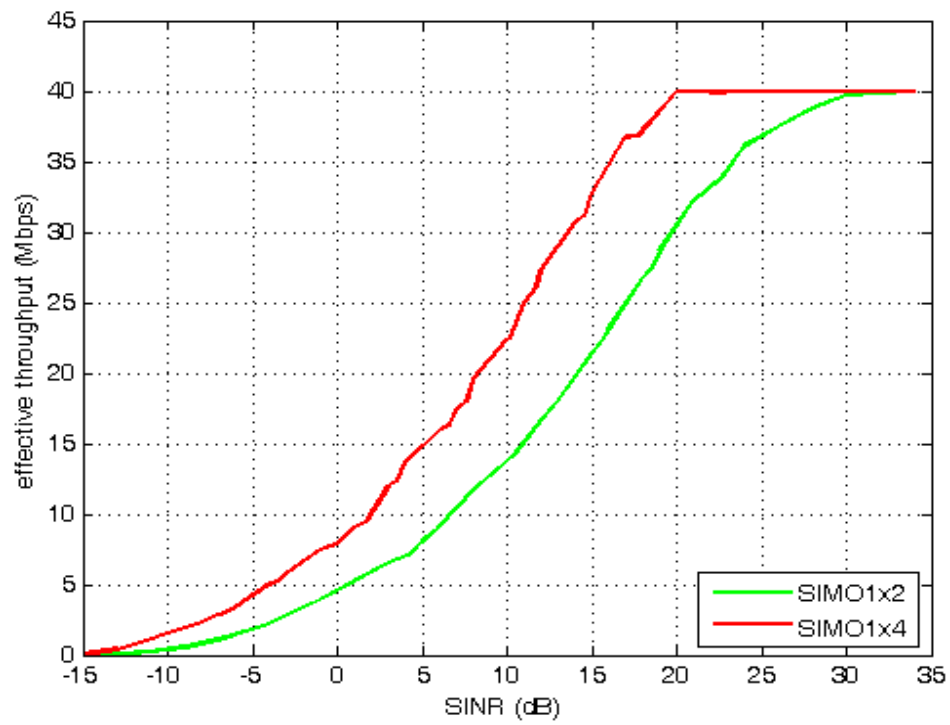Fig. 5 Performance Evaluation of LTE DL for different antenna configurations

Fig. 6 Performance Evaluation of LTE UL for different antenna configurations

III LTE-ADVANCED

III.1   *SIMULATION TOOL EVOLUTION TOWARDS LTE-ADVANCED*

It is important to point out that in LTE-Advanced there will be three type of aggregation scenarios: intra-band contiguous, intra-band non-contiguous and inter-band non contiguous component carrier aggregation. In [15], four transmission architectures are presented to be further investigated.

- Option A. Only one processing chain (baseband + IFFT + DAC +mixer +PA). This option can only transmit in adjacent component carriers.

- Option B. It combines analog baseband waveforms from first component carrier via a mixer operating at an IF of roughly the bandwidth of the other component carrier. The resulting wideband signal is up-converted to RF. This option allows contiguous and non-contiguous intra-band aggregation.

- Option C. This option is similar to option B but it does an IF up-conversion of each component carrier before combining. This option also allows the same performance.

- Finally, the option D employs multiple RF chains and multiple power amplifiers after which the high-power signals are combined and feed into an only antenna. This option allows the three types of aggregation scenarios.

These cases are relative to the transmission chain. In case of the reception there are two different methods:

- Only one chain (RF + FFT + baseband) which processes a bandwidth bigger than 20 MHz but only contiguous component carriers.

- Multiple chains (RF + FFT + baseband) with bandwidth smaller or equal to 20 MHz. This option works with the three types of aggregation scenarios.

Difference in power consumption of DL transmission has been discussed into 3GPP. For instance, in [32] an estimation of the power consumption of the wideband and narrow transmission with some hardware implementation is discussed. Up to now, manufacturers have not reached a definite agreement and hence the LTE-Advanced simulator has to cover the three aggregation scenarios. Therefore, the best solution was to have multiple chains for both transmission and reception. The designee scheme is showed in the Fig. 7.

The configuration of multiple chains is compatible with LTE, and therefore, one of the main 3GPP requirements is achieved. The software implementation complexity will be multiplied by five in the worst-case scenario. Note that the codification scheme of Fig. 7 could fit either turbo or LDPC codes.
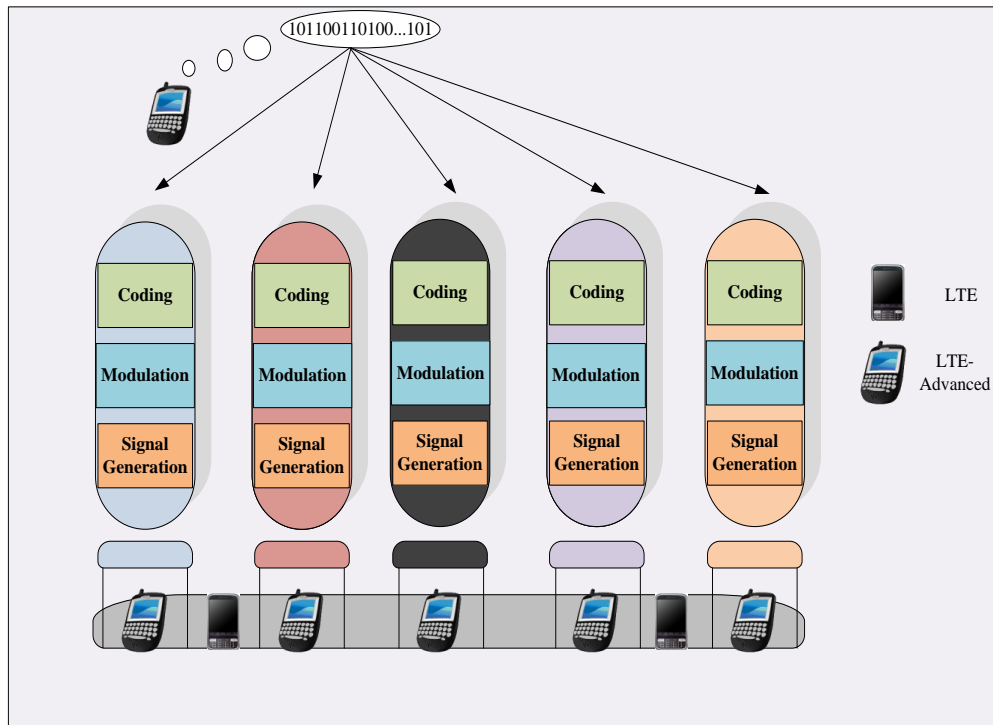
Fig. 7 Designee processing chain for the LTE-Advanced

Another important aspect that shall be included in any IMT-Advanced simulator is the new channel model proposed by ITU-R. This channel model is mandatory in any evaluation of the candidate radio interface technologies for IMT-Advanced. The characteristics of this channel are detailed in next section. On the other hand, the results obtained in Section IV simulate an AWGN channel and, therefore, the IMT-Advanced channel does not have any relevance.

III.2   GEOMETRIC STOCHASTIC CHANNEL MODEL

Realistic modelling of propagation characteristics is essential for two main reasons. First, link and system level performance of LTE-Advanced can be evaluated only when the radio channel models are realistic. Second, the model used for radio propagation plays an important role in the network planning phase of LTE-Advanced deployment.

The propagation characteristics are in a large part affected by the carrier frequency. In November 2007, ITU-R in the World Radiocommunication Conference (WRC-2007) allocated new frequency bands for the IMT radio access between 450 MHz and 3.6 GHz. Now, and according to [33], six are the frequency bands for the E-UTRA:

- 450-470 MHz band,
- 698-862 MHz band,
- 790-862 MHz band,
- 2.3-2.4 GHz band,
- 3.4-4.2 GHz band, and
- 4.4-4.99 GHz band.

In the evaluation of the IMT-Advanced candidates, channel models are of paramount importance to guarantee an accurate modelling of the propagation conditions. The ITU-R has defined in [23] a channel model that can be parameterised to cover all the defined test environments. The proposed model belongs to the family of stochastic models based on the geometry and directions of the rays. Actually, the main features of this model are quite similar to the Extended Spatial Channel Model (SCME) defined by the WINNER project [34] and also described by the 3GPP [35]. According to [23] each transmitter and receiver pair comprises a set of clusters – propagation paths – each containing twenty different rays. Every ray is characterised by a set of parameters, such as angle of arrival, angle of departure, delay and relative power. Finally, the superposition of all these rays results in different correlations among the antenna elements and a geometry-dependent temporal fading.

Given the complexity of this model, the ITU-R has specified in [23] an alternative method based on the usage of a correlation matrix. This simpler channel model combines an environment-specific tapped delay line with Doppler spectrum, with the incorporation of a total covariance matrix per tap in case of Multiple Input Multiple Output (MIMO). Since the 3GPP has also suggested this model for the conformance specification of user equipments [36], this mode was the first implemented in the simulation platform. Next, the complete one was added.

III.3   CARRIER AGGREGATION

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, with contiguous or non-contiguous 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 by 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. In fact, contiguous and non-contiguous component carriers shall be supported where each component carrier is made of 110 resource blocks at the most, what is equivalent to 20MHz bandwidth. The component carriers shall be aligned to the channel raster of 100 kHz and to the separation between subcarriers of 15 kHz.
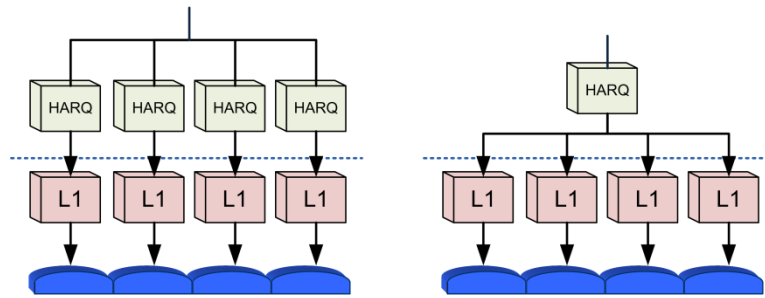
Fig. 8 Two alternatives for the mapping to the component carriers

This will cause that the component carriers have a bandwidth multiple of 300 KHz. Besides, it will be possible to configure a UE in order to aggregate a different number of component carriers that may have different bandwidths in the UL and the DL.

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

An additional alternative was analysed in the framework of LTE-Advanced feasibility study. According to this alternative, only one HARQ process could be used for all bands. The difference between both alternatives is shown in Fig. 8. The main benefit of using only one HARQ process is that the turbo coder is more efficient when the size of the transport block increases. However, if the packet size is too big, any failure in the first attempt transmission entails the retransmission of a large block. This limitation has motivated that the 3GPP adopted the first proposal, i.e. different HARQ processes for any aggregated band (left alternative in Fig. 8).

Another important aspect is related to the downlink signalling control in LTE-Advanced. In the 3GPP's forums four configurations were discussed [37]:

- Option 1: one Physical Downlink Control Channel (PDCCH) in the same carrier that the Physical Downlink Shared Channel (PDSCH).

- Option 2: one PDCCH for each PDSCH located in a component carrier, related to whole bandwidth.

- Option 3: one PDCCH related to whole bandwidth located in a component carrier.

- Option 4: one PDCCH related to whole bandwidth located in each component carriers.
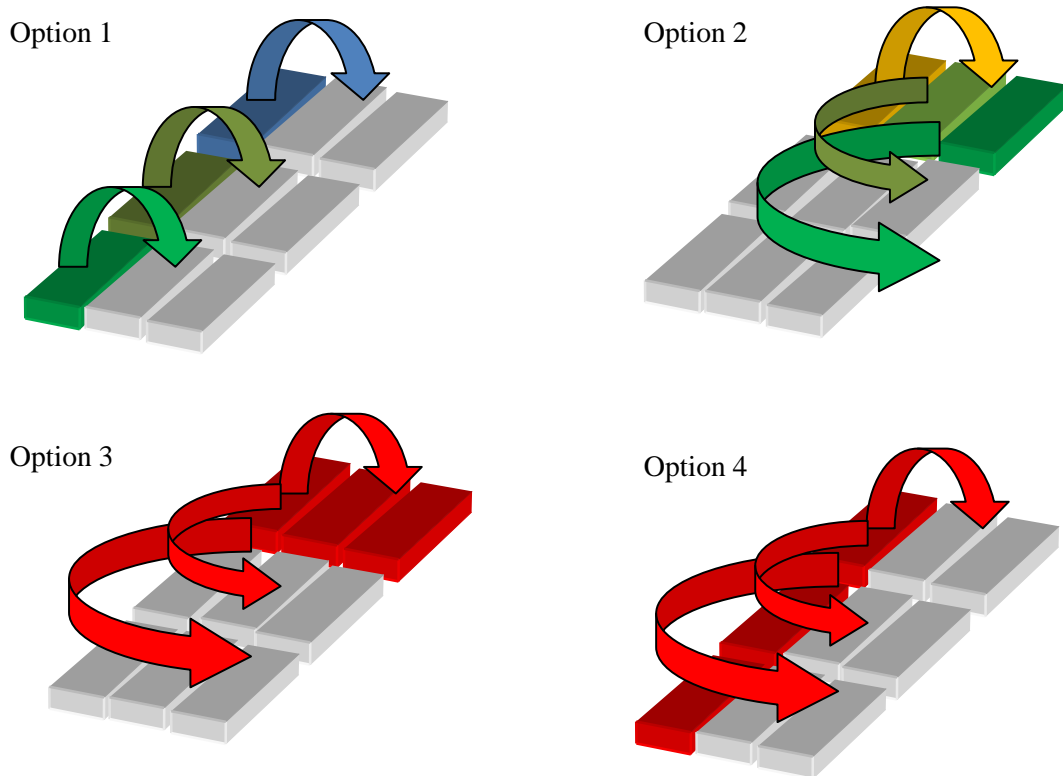
Fig. 9 Configuration for the control signaling

All configurations have advantages and disadvantages but the option 1 is the favourite candidate due to the backward compatibility with LTE (see [37]). However, for the sake of identifying the best choice this Master Thesis will study all possibilities with the objective of finding the most efficient solution. From a view point of saving battery the option 4 is the worst due to the fact that the user should test all the component carriers. The option 2 has several shared properties with the option 1 but it is not clear its improvement. It would need an explicit indication of the component carrier signalized. Finally, option 3 is related with option 2 but it would need new Data Control Indicators (DCI) capable of handling larger resource blocks addressing.

III.4   LDPC

In 1963, Gallager invented the LDPC codes in his PhD thesis [38] and demonstrated that random regular LDPC codes perform close to Shannon limit when the number of bits increases. However, they were soon forgotten until 30 years later because there was not a practical decoding technique. Finally, Mackay and Neal showed empirically that the LDPC codes offer optimum performance with iterative decoding algorithms, just as turbo codes.

LDPC codes can be defined by means of a sparse parity-check matrix H of ones and zeros. The term low density is given that the matrix contains a number of ones small as compared with the number of zeros. The matrix H has dimensions of m rows per n cols, where m is the number

of parity bits and n is the length of the codeword. The number of systematic bits is $k=n-m$. For instance, a possible matrix H is showed in equation (1):

$$H = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix} \qquad (1)$$

This matrix has a representation by means of a bipartite graph which is also called Tanner graph. The graph has two types of nodes: message and check nodes. Each check node corresponds to a row of the matrix H and each message node to a column. The check node i is connected with the message node j at position (i,j) of H. If the matrix has the same number of ones (d_c) per row and the same number of ones (d_v) per column, then the codes is called regular. In general, a regular code is represented as (d_v, d_c)) to indicate that there are d_v.ones per column and d_c per row. Fig. 10 depicts an irregular code due to the fact that all check or message nodes do not have the same number of vertices corresponding to the matrix H of equation (1).
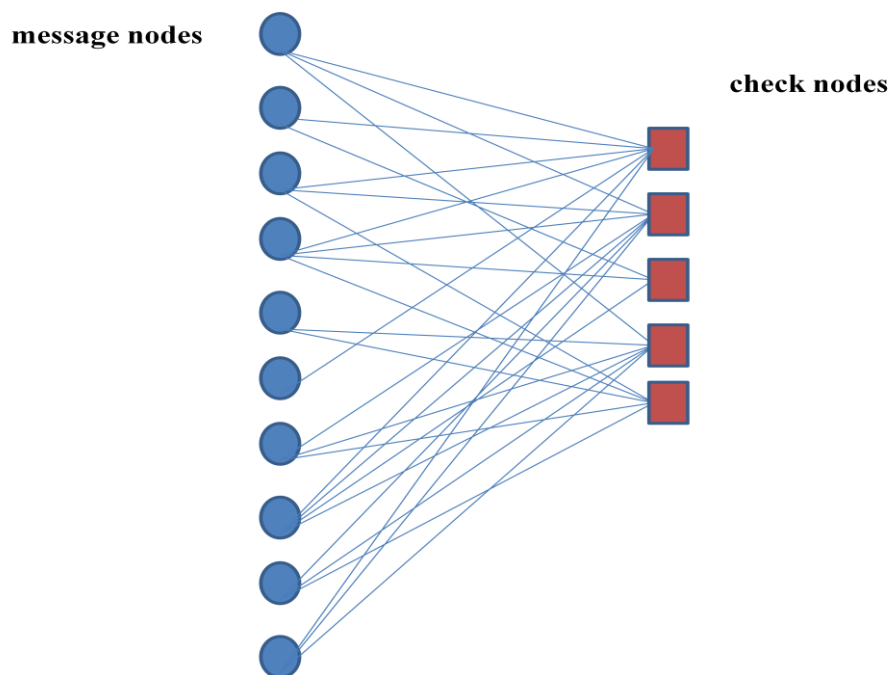

Fig. 10 Equivalent graph representation of an irregular code

There are two important concepts to understand the characteristics of LDPC codes: cycle and girth. A cycle is a sequence of connected vertices which starts and ends in the same node. The length of a cycle is the number of vertices. On the other hand, a girth is the size with the smallest cycle.

The matrices used in the simulator belong to WiMAX standard [4]. The matrix H is expanded from a matrix H_{bm} of size m_b by n_b, where $n = z \cdot n_b$ and $m = z \cdot m_b$. When the matrix H_{bm} contains a zero, the matrix H is expanded with a z by z identity matrix. If it contains a -1 the number is substituted by a z by z zero matrix. Finally, if it contains a number bigger than 0 then the number is replaced by a circular shift $p(i,j)$ in columns of the identity matrix. It is worth highlight to the matrices H_{bm} are defined for a maximum size and rate given. There are six matrices defined for four different rates (1/2, 2/3A, 2/3B, 3/4A, 3/4B and 5/6). Besides, the matrix must be scaled proportionally in function of the follow expression for the code rates of 1/2, 3/4A and B, 2/3B and 5/6:

$$p(f,i,j) = \begin{cases} p(i,j), p(i,j) \leq 0 \\ \left\lfloor \frac{p(i,j)z_f}{z_0} \right\rfloor, p(i,j) \geq 0 \end{cases}, \tag{2}$$

where $\lfloor . \rfloor$ is the floor function that gives the nearest integer towards $-\infty$, . z_f is the expansion factor and z_0 is the biggest expansion factor.

For code rate 2/3A, the scaling is different:

$$p(f,i,j) = \begin{cases} p(i,j), p(i,j) \leq 0 \\ \lfloor p(i,j)z_f \rfloor, p(i,j) \geq 0 \end{cases} \tag{3}$$

The coding using linear codes is obtained by a generator matrix. This matrix can be derived using a Gaussian elimination method. However, it leads to storage and encoding complexity problems. Even though, there are methods that partially solve the problem, since restricting a sub-matrix of the parity check matrix to be lower triangular eliminates the need to derive a generator matrix and leads to linear encoding complexity. For this reason, this group of matrices is used in WiMAX and they are used to encode as in [39].

In the simulator, two types of decoding algorithms have been implemented: sum-product [39] and min-sum [40] decoding algorithms. Both algorithms are based on the propagation of messages among nodes. The purpose of the decoder is to determinate the transmitted values of the bits. The decoding starts by assigning the received channel value of every bit, i.e. the a-priori log-likelihood ratio, to the corresponding message node. Each check node receives the received information of its neighbor message node and then it is processed and sent back. Each message node can perform a hard decision and check if the codeword is a correct codeword by means of this check $x \cdot H^T = 0$. If the expression is not satisfied, then the algorithm can continue some additional iterations.

IV VALIDATION AND ASSESSMENT OF THE INCLUDED FEATURES

After implementing any simulator a validation process must be followed to guarantee the accuracy of results. This process must be rigorous most of all in the first phases since having trustable modules will guarantee the success of future simulations. Currently and to the best of author's knowledge, there is not any paper or report simulating bandwidths up to 100 MHz. Therefore, the simulator will be validated by means of simulation with smaller bandwidths and then it can be extrapolated for bigger bandwidths. Moreover, simulations have been conducted assuming a simple AWGN channel for the sake of easy comparison with the already validated LTE simulator. Recall that the calibration process for LTE is described in [26].

IV.1   VALIDATION OF THE SIMULATOR

In the developing process of the LTE standard, LDPC codes were discussed as a candidate channel coding scheme for both UL and DL. Different performance studies were carried out comparing complexity and effective throughput.

In [17], the performance of 19 LDPC code sizes is studied. This report was chosen for validation due to its rigor. For simplicity reasons, an only block size is going to be considered in the comparison. The parameters of the simulation appear in the Table 2. In Fig. 11 it can be appreciated a maximum difference of 0.1 dB between the simulated curve and the reference curve for the whole range of Signal Noise Ratio (SNR). Therefore, it can be concluded that the LDPC coding has been correctly implemented.

Parameter	Value
Modulation	QPSK
Channel model	AWGN
Rate	1/2
Size of the packet	528
Matrices H	WiMAX [4]
decoding algorithm	Sum-Product
Number of iterations	50

Table 2 Simulation parameters used in the validation of the LDPC codes in LTE
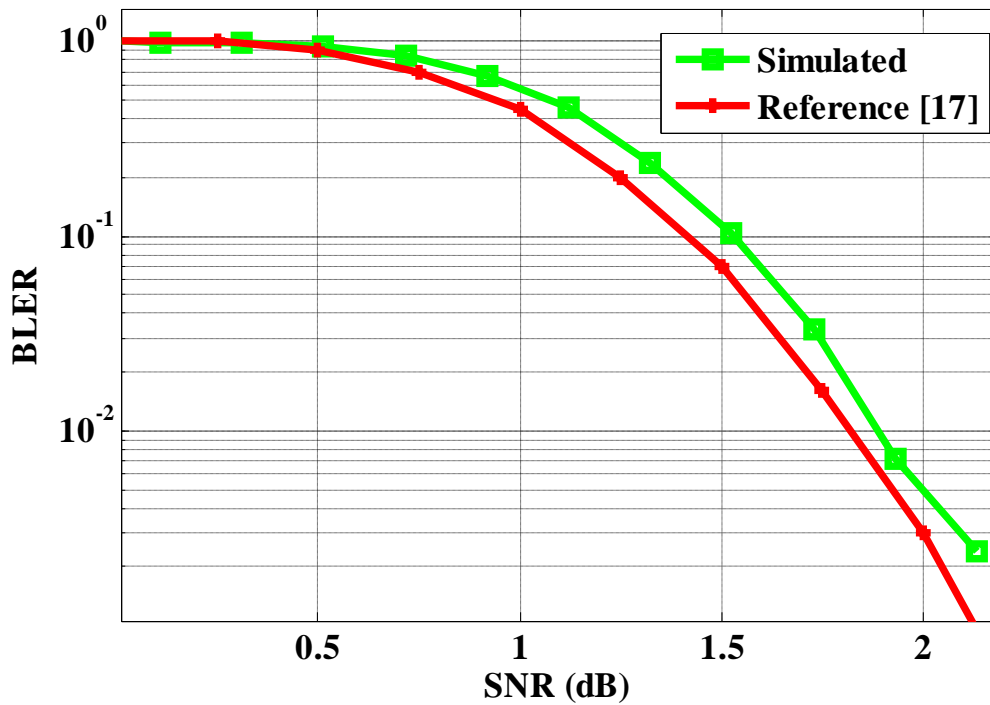
Fig. 11 Validation of the simulator for a rate of 1/2, a size of block of 528 bits and a QPSK modulation.
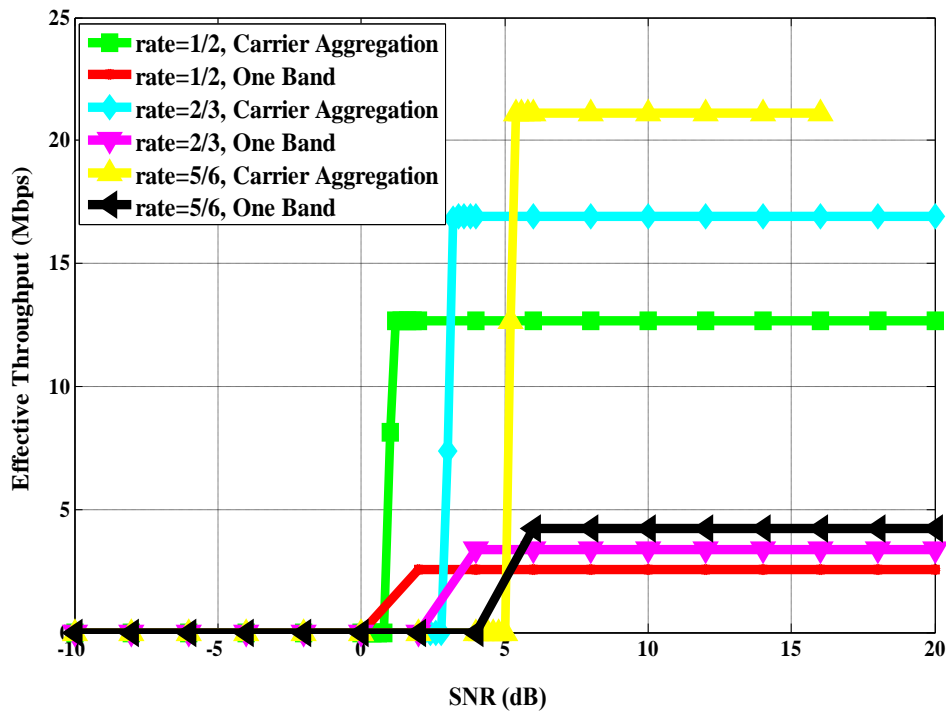
Fig. 12 Spectrum aggregation validation in an AWGN channel and QPSK modulation.

The Fig. 12 depicts the comparison between the throughput of a scenario with five component carriers and a scenario with only one component carrier. One component carrier corresponds to 20 MHz (maximum available bandwidth for the LTE transmission). Different coding rates have been simulated always with a QPSK modulation and assuming an AWGN

channel. In this channel, in absence of multipath effect and variability, the achieved throughput with five chains must be five times the throughput achieved with a processing chain. For instance, for a coding rate 1/2 the maximum throughtput in a band is 2.50 Mbps while with carrier aggregation of five bands the throughput reaches 12.7 The Fig. 12 shows the success of the validation of the simulator with carrier aggregation.

IV.2   *OPTIMIZATION OF THE LDPC CODIFICATION*

The complexity of LDPC decoder depends on the total number of ones of the matrix *H*. Besides, the number of iterations in the LDPC codes, i.e. the number of times that the message nodes and check nodes exchange soft information to increase the probability of correct decoding, increases decoding time. Thus, it is necessary to carry out a study to indentify the optimum number of iterations. The parameters simulated are showed in Table 3. In Fig. 13 and Fig. 14, different rates and number of iterations have been simulated. The results show that starting from 60 iterations for all coding rates the throughput cannot be increased. For a rate of 5/6 with 20 iterations the results are almost as good as for 100 iterations (see Fig. 14). Moreover, a number of iterations smaller than 20 is insufficient to achieve the maximum performance.

Parameter	Value
Modulation	QPSK
Channel model	AWGN
Rate	1/2, 2/3 (B), 5/6
Bandwidth	20 MHZ
Matrices H	WIMAX [4]
LDPC decoding algorithm	Sum-Product
Number of iterations	10 to 100

Table 3 Parameters used in the performance comparison of LDPC codes for different number of iterations.
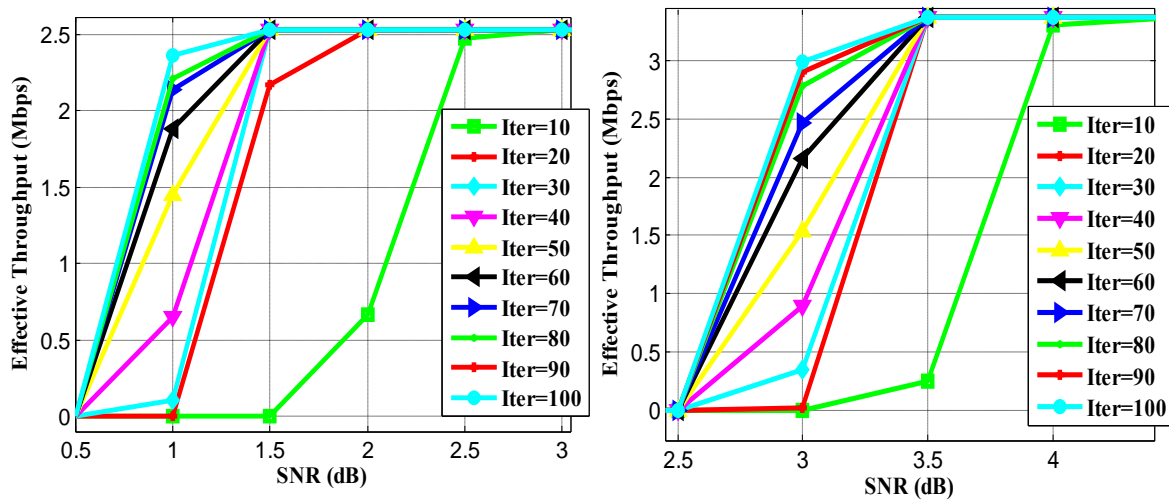
Fig. 13 Variation of the performance with the number of iterations in LDPC codes. QPSK and rate=1/2 (left) or rate =2/3 (right)
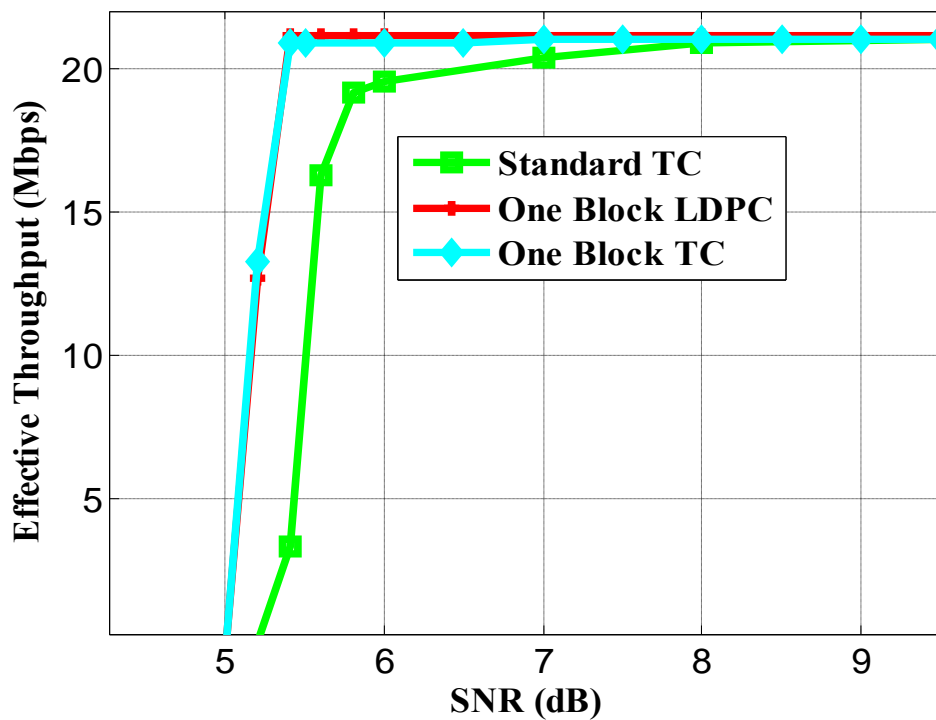
Fig. 14 Variation of the performance with the number of iterations in LDPC codes. QPSK and rate=5/6

IV.3 PERFORMANCE BETWEEN LDPC AND TURBO CODES

LDPC and turbo codes are two codes nearing Shannon limit that can achieve low bit error rates for low SNR applications. The original patent of the LDPC codes has already expired but since March 2001 different patents concerning LDPCs have been applied. Turbo codes were invented

by Berrou in 90's and the patent still exists. Concerning its technological usage, LDPCs is a hot research topic at many universities and there is no common implementation available. However, turbo codes dispose of a well established and implemented technology. Turbo decoders are already available for ASIC and in FPGAs. The performance of LDPC codes increases when the block size increases. Turbo codes have good performance for all block sizes once a certain minimum length is surpassed.

Mobile WiMAX (802.16e) uses LDPC codes while LTE uses turbo codes. The next step towards the 4G will support bandwidths up to 100 MHz. Therefore, the number of transmitted bits will increase. In this point, the first important topic is to decide whether it is better to encode with LDPCs or with turbo codes with such large bandwidths. Another open question in case of turbo coding is if it is better to encode the entire block or to divide the packet in sub-blocks. All these questions are going to be answered in this section considering bandwidths from 20 to 100 MHz.

For all rates and all modulations in a bandwidth of 20MHz the difference of performance (Fig. 15, Fig. 16 and Fig. 17) is lower than 0.5 dB as maximum. The parameters of simulation are listed in Table 4. Depending on the coding rate and the modulation, this difference is more or less notable. However, this difference has a relative importance due to its value. The most important conclusion is that both LDPC and Turbo code performance are very similar for this size of block. It is possible that, with a longer bandwidth, the performance of the LDPCs could be better than the Turbo codes. However, Fig. 18 and Fig. 19 demonstrate that the difference is still insufficient to conclude that a scheme is better than another.

Parameter	Value
Modulation	QPSK/QAM16/QAM64
Channel model	AWGN
Channel coding	LDPC/Turbo codes
Rate	1/2, 2/3, 5/6
Bandwidth	20 MHz/100 MHz
Matrices H	WiMAX [4]
Decoding algorithm	Sum-Product
Number of iterations	100 (LDPC)/8 (Turbo)
Retransmissions	0
Segmentation	No(LDPC)/Yes (Turbo)

Table 4 Basic parameters of the comparison of the performance between LDPC and Turbo codes for bandwidth of up to 20 MHz and 100 MHz.
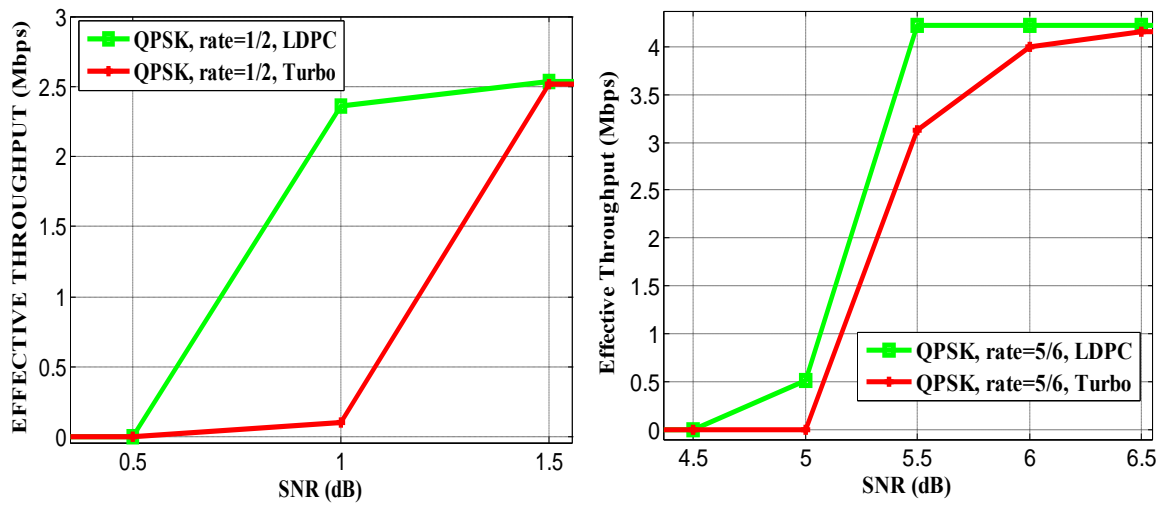
Fig. 15 Performance comparison between LDPC and turbo codes for [15156 bits, rate=1/2] (left) and [25276 bits, rate=5/6] (right) in a QPSK modulation
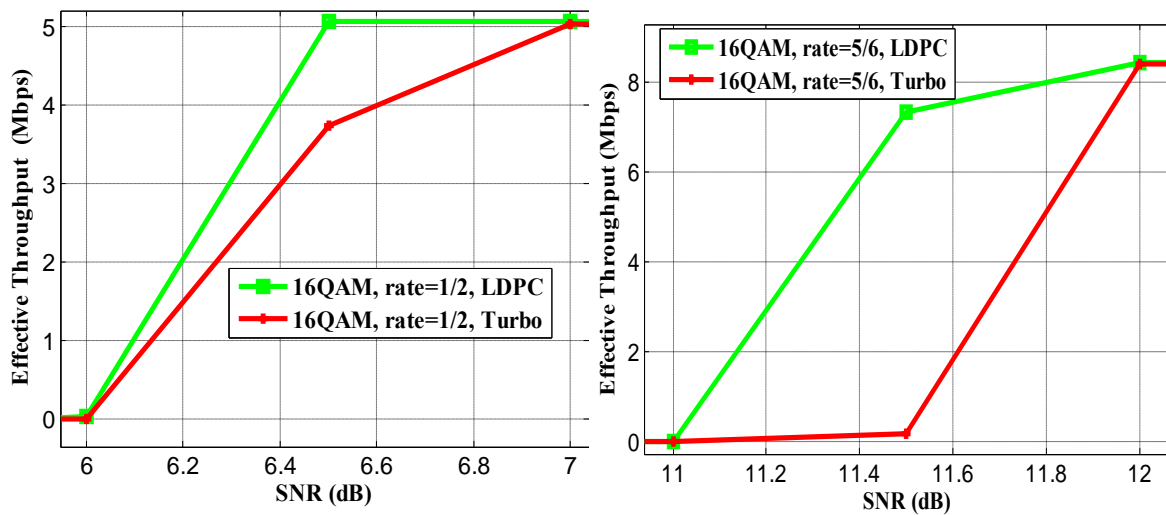
Fig. 16 Performance comparison between LDPC and turbo codes for [30336 bits, rate=1/2] (left) and [50576, rate=5/6] (right) in a 16QAM modulation.
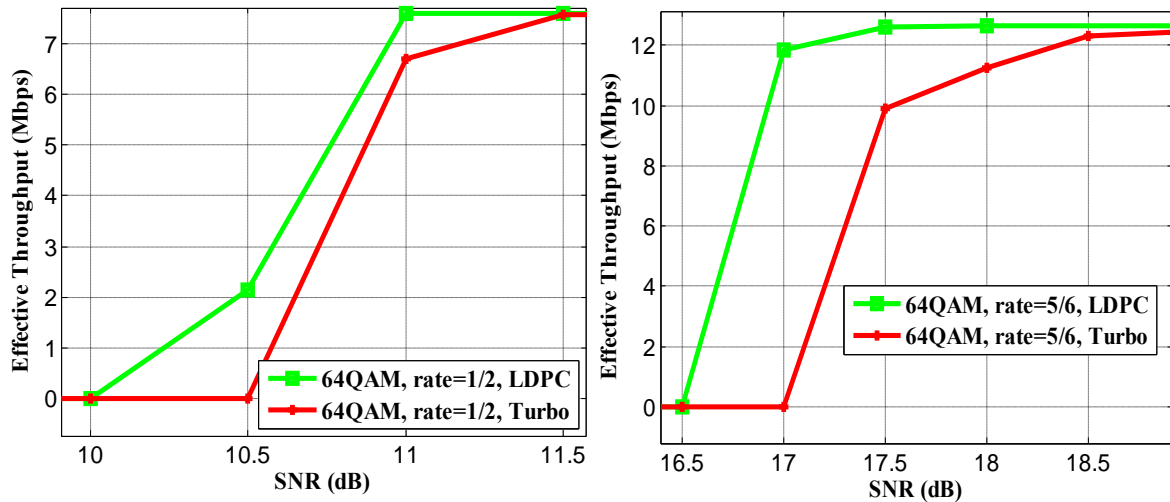
Fig. 17 Performance comparison between LDPC and turbo codes for [45516 bits, rate=1/2] (left) and [75876 bits, rate=5/6] (right) in a 64QAM modulation

Given the current technology, the processing capacity of mobile is limited. This is why, in the current standards using turbo codes, before encoding there is a stage of segmentation of the transport block coming from the Medium Access Control (MAC) layer. In LTE, when a transport block is bigger than 6144 bits the packet is segmented. In WiMAX Mobile (802.16m) the size is 4800. However, some simulations have been executed to check if this limitation should be eliminated in case of technological evolution. Since the LTE interleaver only works for sizes up to 6144 bits, in case of non-segmentation the interleaver is random. Simulation results indicate that the difference considering the non-segmentation is lower than 0.25 dB. Besides, when transport blocks are not divided the difference between both coders is negligible.

Fig. 18 Performance comparison between turbo codes with packets no larger than 6144, turbo codes with only one turbo block and LDPC codes for [75876 bits, rate=1/2] (left) and [101176 bits, rate=2/3] (right) and a QPSK modulation.

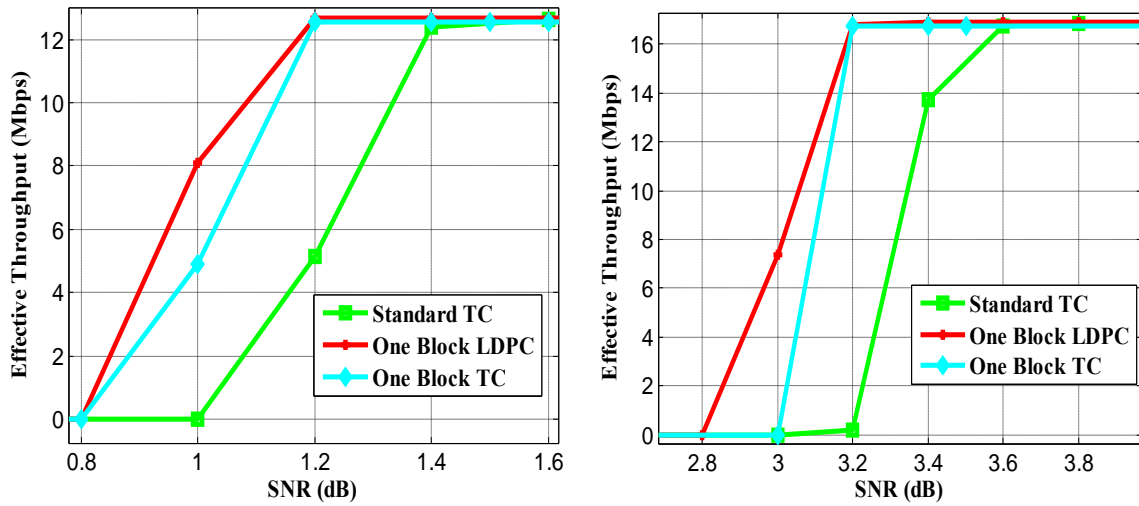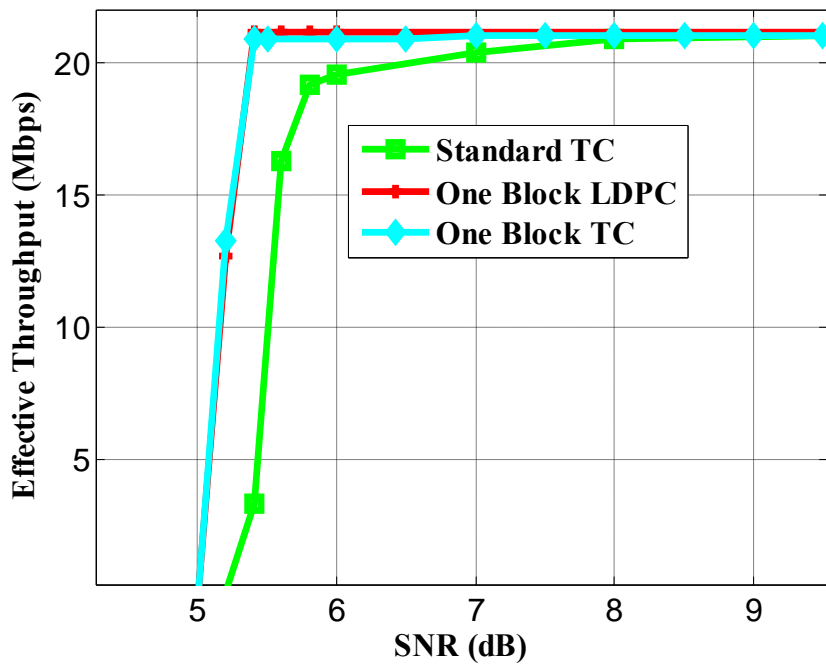Fig. 19 Performance comparison between turbo codes with packets no larger than 6144, turbo codes with only one turbo block and LDPC codes for [126476 bits, rate=5/6] and a QPSK modulation.

V   CONCLUSIONS AND FURTHER WORK

In this Master Thesis, the fourth generation 3GPP technology known as LTE-Advanced have been partially implemented and evaluated. Given that the standard is still not available, this implementation was restricted to some basic properties that nowadays grab most of the research attention, that is, carrier aggregation and channel coding alternatives. Besides, a previous LTE simulator, already developed by the author in a previous stage, has been adapted and extended following the new radio access features defined in the Release 8. Some of the new characteristics included in the now completed LTE simulator are: MIMO processing, realistic control signaling overhead and all the transmission and reception chain in the uplink. Moreover, a calibration procedure has been defined, working in parallel with other partners in WINNER+, allowing a complete validation of the LTE simulator. Finally, the simulator in downlink and uplink was also calibrated with the main manufacturers participating in 3GPP, most of all, Nokia Siemens Networks and Ericsson.

The core of the dissertation was the adaptation of the LTE simulator to LTE-Advanced. The research was focused on the viability of using LDPC codes with longer size blocks. Previous studies show that LDPC codes are a good solution to reach the high data rates required by new applications like video on demand, videoconference, file downloading, etc. However, the difference in performance does not reach 0.5 dB between LDPC and turbo codes. Therefore, turbo codes continue being an appropriate solution in the next technologies of radio access network. Hence, the election of the codification scheme will be based on its complexity. The LDPC codes have a simpler implementation due to the fact that the computation cost of an iteration in turbo codes is bigger than LDPC codes. Besides, the acquired experience for previous systems like UMTS or LTE implies a clear advantage with respects to LDPC codes. However, the license of turbo codes has not expired yet and it entails an additional cost for the manufacturers. This research implies a challenge for international scientific community, in the same way as Berrou and Glavieux, who made history with the discovery of turbo codes. Several times the implementation of a scheme or another is chosen for political reasons. This is why it is so important to analyze the advantages or disadvantages of the proposal schemes by external organisms like WINNER+. On the other hand, different studies to optimize the LDPC codes have been realized. For instance, the number of iterations between message and check nodes or the type of decoding algorithm has been checked. The drawn conclusion is that 60 iterations is a good trade-off between performance and complexity. Finally, Sum-Product algorithm is better than Min-Sum algorithm, although the differences for different coding rates are not very relevant, and therefore, it will depend on the facility for implementation.

Obviously, further work is oriented to the enhancement of IMT-Advanced technologies which is a hot topic in today's research trends supposes a permanent challenge for the international scientist community. Particularly, the author is interested in the main features of the spectrum aggregation, paying special attention to the optimization of the radio access network. The research is not only headed for LTE-Advanced, rather it can be aimed at other mobile communications systems like WiMAX.

ACKNOWLEDGEMENTS

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ANNEX A

Título del proyecto: ADVANCED LONG TERM EVOLUTION UNICAST AND MULTICAST JOINT RESOURCE ALLOCATION (TEC2008-06817-C02-01)

Entidad financiadora: MINISTERIO DE CIENCIA E INNOVACION

Duración desde: 01/01/2009   **Hasta:** 01/01/2012

Investigador principal: CARDONA MARCET, NARCIS

Importe de la subvención: 163.592   **Nº total investigadores del proyecto:** 6

Título del proyecto: DESARROLLO DE ALGORITMOS DE ASIGNACION DINAMICA DE RECURSOS PARA EL SISTEMA DE COMUNICACIONES MOVILES 3G LONG TERM EVOLUTION (PAID-06-08-3301)

Entidad financiadora: UPV. VICERRECTORADO DE INVESTIGACION

Duración desde: 04/12/2008   **Hasta:** 04/12/2010

Investigador principal: Monserrat Del Rio, Jose Francisco

Importe de la subvención: 12.030   **Nº total investigadores del proyecto:** 4

Título del proyecto: CARACTERIZACION DEL ENLACE RADIO EGPP LTE Y EVALUACION DE SUS PRESTACIONES (GVPRE/2008/247)

Entidad Financiadora: CONSELLERIA DE EDUCACION

Duración desde: 01/01/2008   **Hasta:** 01/01/2009

Investigador Principal: Monserrat Del Rio, Jose Francisco

Importe de la subvención: 6.865,5   **Nº total investigadores del proyecto:** 5

ANEXO B

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

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Abstract

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 previous 3G standard. However, this paper also demonstrates that LTE performance does not fulfils 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.

Keywords

LTE, IMT-Advanced, 4G, Performance, 3GPP

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), etc. 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 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, what 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 (IMT)-Advanced, following the same model of global standardization used with the Third Generation, IMT-2000. The objective of this initiative is to

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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 need 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 1x1 multiantenna scheme for the downlink and Release 6 HSUPA with a 1x2 multiantenna scheme in uplink.

For the sake of comparison, in LTE it is considered transmission using up to 2x2 antennas in downlink and up to 1x2 antennas in uplink.

Among others, LTE design targets are:

- The system should support peak data rates of 100 Mbps in downlink and 50 Mbps in uplink within a 20MHz 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.

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

- 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.

- 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.

- Mobility up to 350 km/h.

- 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.
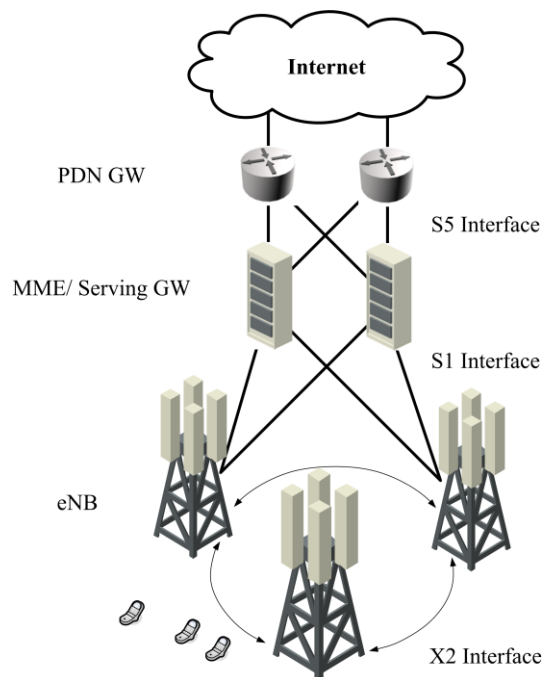

Figure 1. LTE Release 8 architecture

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:

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

- 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.

- 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.

- 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 multi-carrier 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 inter-symbol 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.

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 respectively).

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, non-overlapping 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 multi-codeword 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 turbo code 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, etc. 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, etc. while link to system level models are 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] and [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] and [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 20MHz the maximum achievable rates in downlink are: 91.2 Mbps for SIMO 1x2, 172.8 Mbps for MIMO 2x2 and 326.4 Mbps for MIMO 4x4. The resulting peak spectral efficiencies are 4.56, 8.64 and 16.32 b/s/Hz for the considered multi-antenna 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 1x2 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.
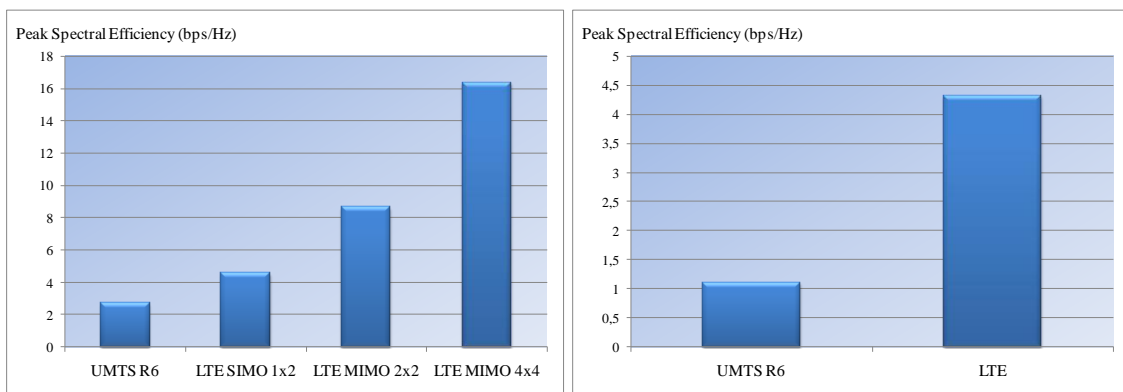

Figure 2. LTE peak spectral efficiencies in downlink (left) and uplink (right)

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, i.e. including HSDPA and HSUPA. From this peak spectrum efficiency it can be seen that LTE with 20MHz meets and exceeds the 100Mbps downlink and 50Mbps 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 5Hz. The central frequency has been set to 2.5GHz, 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 multi-antenna configuration at the receiver side, minimum mean-square error (MMSE) equalization was considered. The remaining parameters considered in the simulations are summarized in Table I.

Concerning LTE downlink, different multi-antenna configurations were modeled including SIMO 1x2, MIMO 2x2 and MIMO 4x4. Simulated MIMO scheme followed the open loop spatial multiplexing scheme as specified by the 3GPP [16], the number of codewords were 2 and the number of layers was equal to the number of transmit antennas, i.e. 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 were considered.

In the uplink, two different multi-antenna configurations were simulated: SIMO 1x2 and SIMO 1x4. 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.

Table I. Simulation parameters

Common parameters		
Bandwidth	10 MHz (50RB)	
Channel	Tapped delay line: EPA with 5Hz Doppler frequency at link level, ETU at system level.	
Central frequency	2.5 GHz	
MCS	CQI 1 – 15	
Multi-antenna schemes	DL	SIMO 1x2, MIMO 2x2 / 4x4
	UL	SIMO 1x2 / 1x4
Control channels overhead	DL	2 OFDM symbols per subframe
	UL	not considered

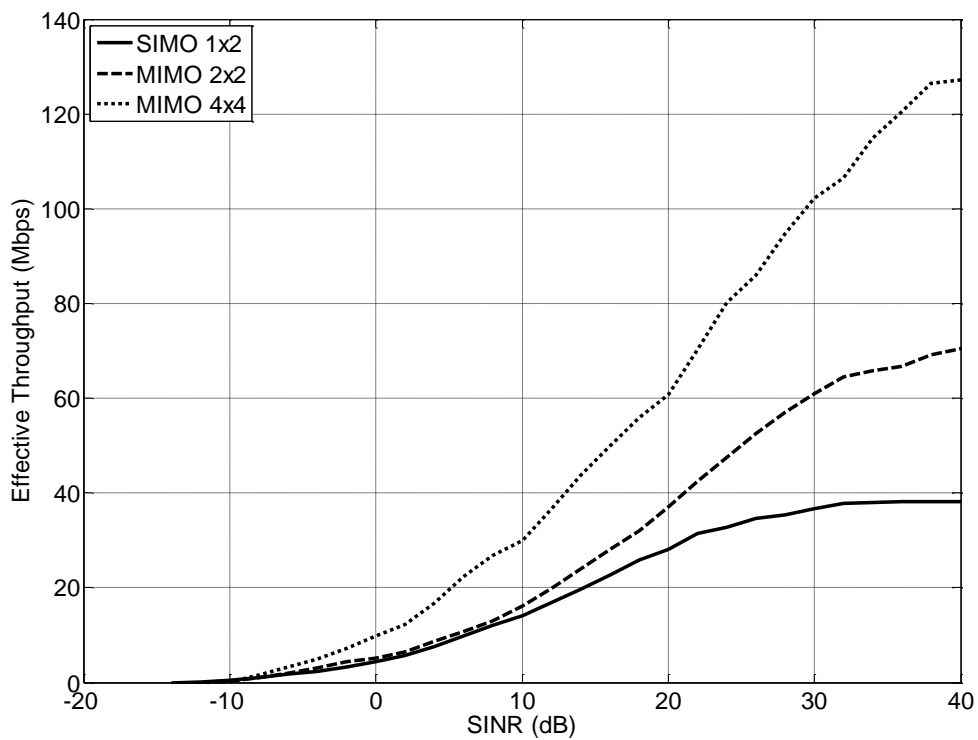| System level parameters	
Inter Site Distance (ISD)	500m
Cell deployment	3-sector cells, reuse 1
Pathloss	130.2+37.6 log10(d(km)) dB
Shadowing	lognormal, $\sigma = 8$dB
eNB transmission power	46dBm
Noise spectral density	-174 dBm/Hz
Scheduler	Proportional Fair in time and frequency domains up to 5 UEs are scheduled per subframe
Mobility	Users moving at 30 km/h

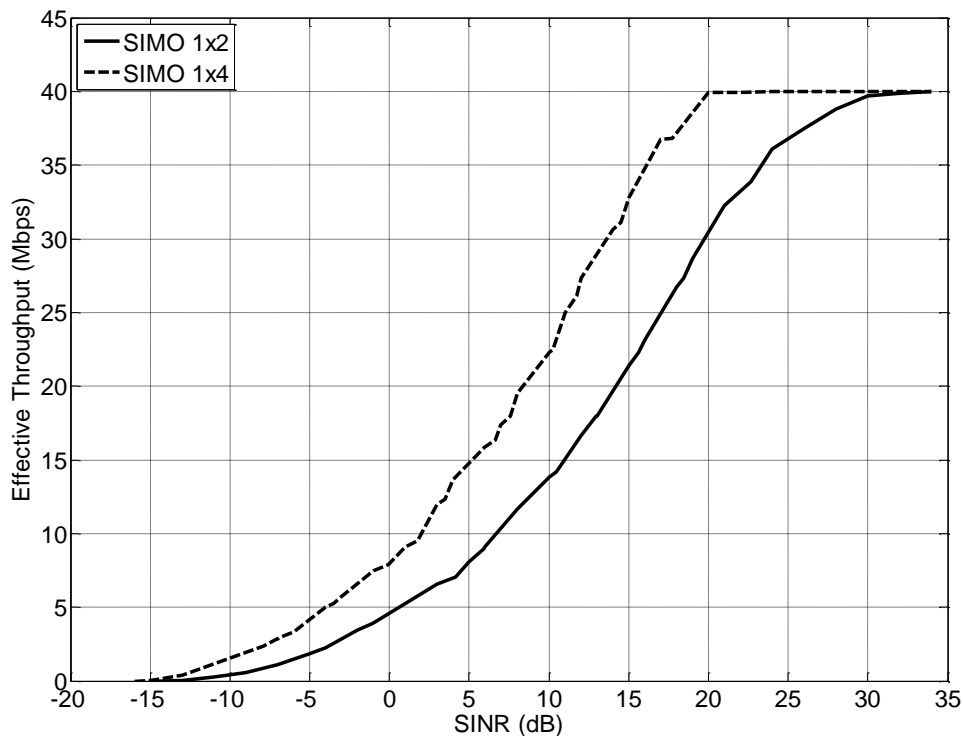**Figure 3.** Link level evaluation of throughput vs SINR in LTE downlink

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

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 20MHz 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 4x4 scheme provides a clearly better performance than the other schemes for almost all the useful SINR margin. Nevertheless, MIMO 2x2 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 2x2 and MIMO 4x4 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 non-negligible SINR gain can be achieved. This gain is about 5 dB for a throughput of 20 Mbps. Note that in SIMO 1x4 maximum rate is achieved 10 dB before than in SIMO 1x2.

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 I. 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 1x2, 1.70 bps/Hz/cell for MIMO 2x2 and 2.50 bps/Hz/cell for MIMO 4x4. 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 relative to HSPA performance, Table II includes HSPA figures extracted also from [12] and [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.

Table II. LTE requirements related to technical performance

		Requirements LTE TR 25.913	LTE simulation results
Peak Data Rate (Gbps)		0.1	0.172 (2x2) 0.326 (4x4)
Latency		C-Plane <100ms U-Plane <5ms	-
Peak Spectral Efficiency (bps/Hz)	DL	5 (1x2)	4.56 (1x2) 8.64 (2x2) 16.32 (4x4)
	UL	2.5 (1x2)	4.32 (1x2)
Average Spectral Efficiency (bps/Hz/cell)	DL	EUTRA (2x2) 3-4 times HSDPA R6 {0.53}	1.52 (1x2) 1.70 (2x2) 2.50 (4x4)
	UL	EUTRA (1x2) 2-3 times HSUPA R6 (1x2) {0.332}	0.73 (1x2)
Cell Edge User Spectral Efficiency (bps/Hz/cell/user)	DL	EUTRA (2x2) 2-3 times HSDPA R6 {0.02}	0.02 (1x2) 0.04 (2x2) 0.05 (4x4)
	UL	EUTRA (1x2) 2-3 times HSUPA R6 (1x2) {0.009}	0.02 (1x2)
Mobility		up to 350 km/h	30 km/h
Bandwidth		up to 20 MHz	10 MHz

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 candidate 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:

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

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

- 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.

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]:

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

- 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 10ms to get synchronized and the scheduler should reduce the U-plane latency at maximum.

- 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 8x8 or less in DL and 4x4 or less in UL.

- The 3GPP defined a base coverage urban scenario with inter-site distance of 500m and pedestrian users. Assuming this scenario, average user spectral efficiency in DL must be 2.4 bps/Hz/cell with MIMO 2x2, 2.6 bps/Hz/cell with MIMO 4x2 and 3.7 bps/Hz/cell with MIMO 4x4, whereas in UL the target average spectral efficiency is 1.2 bps/Hz/cell and 2.0 bps/Hz/cell with SIMO 1x2 and MIMO 2x4, respectively.

- In the same scenario with 10 users, cell edge user spectral efficiency shall be 0.07 bps/Hz/cell/user in DL 2x2, 0.09 in DL 4x2 and 0.12 in DL 4x4. In the UL, this cell edge user spectral efficiency must be 0.04 bps/Hz/cell/user with SIMO 1x2 and 0.07 with MIMO 2x4.

- 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.

- 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.

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

Next table 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.

Table III. 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 <100ms U-Plane <10ms	C-Plane <50ms U-Plane <5ms
Peak Spectral Efficiency (bps/Hz)	DL	15 (4x4)	30 (8x8)
	UL	6.75 (2x4)	15 (4x4)
Cell Spectral Efficiency (bps/Hz/cell)	DL	2.2 (4x2)	2.4 (2x2) 2.6 (4x2) 3.7 (4x4)
	UL	1.4 (2x4)	1.2 (1x2) 2.0 (2x4)
Cell Edge User Spectral Efficiency (bps/Hz/cell/user)	DL	0.06 (4x2)	0.07 (2x2) 0.09 (4x2) 0.12 (4x4)
	UL	0.03 (2x4)	0.04 (1x2) 0.07 (2x4)
Mobility		up to 350 km/h	up to 350 km/h
Bandwidth		> 40 MHz	up to 100 MHz

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, non-contiguous 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 20MHz. For instance, a user receiving information in 100MHz bandwidth will need 5 receiver chains, one per each 20MHz block.

Coordinated multiple point transmission and reception

Coordinated multi point transmission and reception is 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, pre-processing 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, i.e. 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 Multi-User (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 150Mbps in the downlink and 40Mbps in the uplink with 10MHz bandwidth. Besides, in the downlink the minimum average throughput will be around 30Mbps, 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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MAC Layer Performance of Different Channel Estimation Techniques in UTRAN LTE Downlink

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Abstract— **Long Term Evolution (LTE) is the new standard proposed by the 3GPP to evolve towards 4G. Evolved UTRAN (E-UTRAN) specifications are currently completed and research groups are studying the performance of the last Release 8. Nevertheless, these studies lack a full modeling of the MAC layer because they either leave out retransmissions and turbo coding or assume ideal channel estimation. This paper uses an accurate LTE MAC layer simulator to perform a complete downlink LTE performance study. Results compare different channel estimation techniques showing significant difference among them, most of all regarding the robustness of the estimator against errors. Finally, LTE system performance assessment is presented employing a realistic channel estimator.**

Keywords-LTE; channel estimation; link level simulation

I. INTRODUCTION

Mobile communications with improved transmission capabilities are important economical and social drivers generating growth. The UTRAN Long Term Evolution (LTE) is an ongoing task to build up a framework for the evolution of the 3rd Generation Partnership Project (3GPP) radio technologies towards 4G. In March 2008, 3GPP approved the specifications of the Evolved UTRAN (E-UTRAN) and research community is currently assessing the performance of the definitive Release 8 standard.

E-UTRAN is based on the Orthogonal Frequency Division Multiplexing (OFDM) technique, especially suited for combating multipath fading, offering higher spectral efficiency than previous 3GPP technologies. Accurate channel estimation in OFDM systems, and hence in LTE, allows coherent demodulation and improves system performance. Although several channel estimators have been proposed in the literature, minimum mean-square-error (MMSE) estimators, also referred to as Wiener-based estimators, have been proven to be the optimal linear estimators [1]. MMSE channel estimators use frequency-domain and time-domain correlation functions to filter a set of available estimates obtained with the help of reference signals. Nevertheless, these correlation functions are unknown a priori and must be estimated. MMSE and other simpler channel estimation schemes have been extensively studied in the literature but without considering the specific features and requirements of LTE.

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 turbo coding [2]-[4]. System level analysis need 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 evaluates LTE link level performance considering a transmission chain fully compliant with LTE Release 8 and including realistic HARQ and turbo-decoding. Besides, a number of channel estimation methods apart from the well-known ideal have been compared, including the simplest linear method and those based on Wiener filtering. Special attention has been paid to robustness of Wiener-based channel estimation methods against failures in their assumptions, being this issue not yet assessed in the literature.

The rest of the paper is organized as follows. Section II explains the main radio interface features of LTE. The fundamentals of the implemented channel estimators are presented in section III. Simulation environment is detailed in section IV, whereas simulation results concerning robustness of estimators and global LTE performance are presented and discussed in section V. Finally the main conclusions of the assessment are drawn.

II. LTE RELEASE 8 MAIN FEATURES

3GPP LTE is the name given to the new standard developed by 3GPP to cope with the future market requirements identified by ITU. To meet these requirements, a combination of new system architecture together with an enhanced radio access technology was incorporated in the specifications.

The most important technologies included in the new radio access network are OFDM, MIMO, turbo coding and hybrid ARQ with soft combining. These technologies are shortly explained in the following paragraphs.

A. OFDM

OFDM provides a high robustness against frequency selective fading and offers spectrum flexibility which facilitates a smooth evolution from already existing radio access technologies to LTE. Besides, OFDMA, the multiple access technique derived from OFDM, offers a high degree of freedom to the scheduler. OFDM resources can be represented as a time-frequency grid. Fig.1 depicts the smallest resource unit, the Resource Block (RB). In time domain, one RB

corresponds with one subframe of 1ms, which is divided into 2 time slots each of 7 OFDM symbols. In the frequency domain, each RB consists of 12 subcarriers.

B. MIMO

One of the most important means to achieve the high data rate objectives for LTE is multiple antenna support. LTE supports one, two or four antennas in the transmitter and/or the receiver. Multiple antennas can be used in two different ways: to obtain additional transmit/receive diversity or to get spatial multiplexing by creating several parallel channels. Processes to implement transmit diversity and spatial multiplexing are specifically included in the LTE transmitter specifications [8].

C. 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), the channel studied in this paper, a turbo encoder with rate 1/3 is used, followed by puncturing to increase the coding rate to the desired level.

D. Hybrid ARQ with soft combining

Hybrid Automatic Repeat reQuest (ARQ) with soft combining is a technique that deals with the retransmission of data in case of errors. It consists of a combination of Forward Error Correction (FEC) and 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.

III. CHANNEL ESTIMATION

In a mobile communication system, when the channel is fully known by the receiver the Shannon limit can be approached. However, in real systems, channel is unknown and therefore it has to be estimated. Channel estimation is a difficult task, especially in wideband mobile channels due to their frequency selectivity and time varying nature. In LTE, a pilot-assisted channel estimation is done, since reference signals are used by the receiver to estimate attenuation and phase change suffered by the signal in the frequency domain. Relying on channel estimates frequency domain equalization (FDE) can be performed which is a simple method to correct changes introduced by the channel in the transmitted data.

A. Reference signals

In LTE there exist three downlink reference signals: cell specific, Multicast Broadcast Single Frequency Network (MBSFN) and User Equipment (UE) specific reference signals [8]. Cell specific reference signals are used for the channel estimation and are transmitted on one or several antennas. Their exact position depends on the slot number within a radio frame (10 subframes), the OFDM symbol number within the slot and the type of cyclic prefix. A pseudo-random sequence is used for the reference signal generation.

The resource elements used for the reference signal transmission in any of the antennas will not be used for any transmission on any other antennas in the same slot.
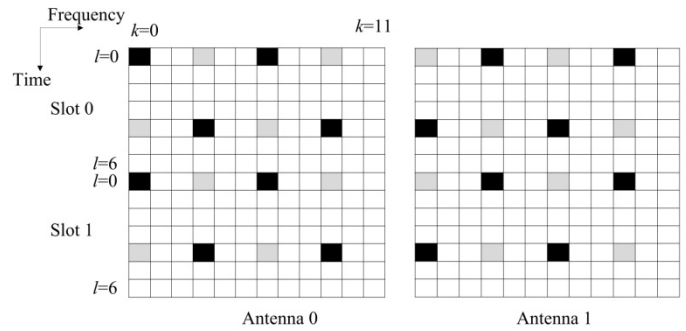

Figure 1. Mapping of the reference signals (normal cyclic prefix)

Fig. 1 illustrates the resource elements selected for the transmission of pilot symbols within one RB and considering two antennas and normal cyclic prefix.

B. Channel estimation methods description

Let $H(l, k)$ be the complex value of channel estimate in the l-th OFDMA symbol and the k-th subcarrier of a RB. In the pilot symbols, $\tilde{H}(l, k)$ is calculated by dividing the received signal, $Y(l, k)$, by the transmitted symbols, $X(l, k)$, which are known:

$$\tilde{H}(l, k) = Y(l, k)/X(l, k) \qquad (1)$$

The remaining complex channel values are obtained from methods which are based on either polynomial or Wiener interpolation (MMSE estimator) or mixed polynomial-Wiener methods. A noticeable characteristic of mobile wireless channels is that their response variation can be assumed to be independent in time and frequency domains. Thus, the correlation of the channel frequency response at different times and frequencies can be calculated as the multiplication of the time and frequency correlation functions. This fact allows a separate time and frequency domain channel estimation instead of the more complex joint time-frequency domain estimation. For this paper, all channel estimation methods are applied first in the frequency domain and then in the time direction. Moreover, a quasi ideal method of channel estimation has been implemented. Next, implemented methods are described:

1) Polynomial interpolation. The polynomial interpolation calculates channel complex symbols between reference signals through a linear or a second-order interpolation [9]. In this paper a completely linear interpolator in frequency and time domain (Linear) has been analyzed.

2) Wiener interpolation. In the OFDM systems the optimal linear estimator in the mean-square error sense is a 2D (both time and frequency) Wiener filter. However, the complexity of this estimator is usually too high to be implemented in practice. The use of separable filters is a common method to reduce complexity with a slight error in performance (W2x1D). The final estimation of the channel attenuations, $\tilde{H}(l, k)$, are linear combinations of the estimates obtained for the pilot symbols. First in the frequency domain, all estimated reference signals within one OFDM symbol are arranged in a vector p. The channel response for a given time and for all subcarriers is a vector, $\tilde{H}_f(l)$, that can be estimated as:

$$\tilde{H}_f(l) = \left(\left(R_{pp} + \sigma^2 I\right)^{-1} R\right)^{\mathrm{H}} p, \qquad (2)$$

where R_{pp} is the autocorrelation matrix of the true channel response at pilot positions, R is the cross-correlation of the channel response and itself at pilot positions, σ^2 is the noise power, H is the hermitian operation, and I is the identity matrix. Once calculated the channel estimates for all subcarriers, in the time domain and for each subcarrier, a similar procedure is followed. In this case, p comprises four estimates taken from those symbols containing reference signals (in Fig. 1 l=0 and l=4 for slot 0 and 1). $\tilde{H}_t(k)$ is calculated as in (2). In both cases, matrices R_{pp} and R are calculated from the frequency and time correlation functions of the channel. The frequency correlation is determined by applying an FFT of the power delay profile, whereas the time correlation fits the zero order Bessel function:

$$R_h(\tau) = J_0(2\pi\tau\nu/\lambda), \qquad (3)$$

where ν is the receiver velocity, λ is the wave length and τ represents the delay. Note that the Wiener interpolation estimator requires a previous knowledge of the frequency and time correlation and the noise power.

3) Mixed polynomial-Wiener methods. In this case a linear estimation in the time direction is used instead of the Wiener interpolation (WFD-LTD). Reduction in the computation complexity is remarkable although it comes at the cost of an error made in the estimation. Additionally, vector p can contain all pilot symbols in an OFDM symbol or just the nearest ones. Both methods are compared in this paper. In the latter, called Wiener low complexity (Wlc), the nearest six pilot symbols are used. This method reduces complexity in exchange for a slight reduction in performance.

4) Quasi ideal estimation. Quasi-ideal estimation (Qideal) has been implemented for the sake of comparison with the best possible results. This method obtains the frequency channel response applying the FFT over the mean value of the channel impulse response every OFDM symbol time interval. This method would be ideal if the channel remained unchanged during the whole OFDM symbol.

IV. SIMULATION ENVIRONMENT

In this assessment, a number of simulations were conducted with a LTE link level simulator fully compliant with the released specifications [8][10]. Next, the main simulator features and simulation assumptions are commented.

A. Frame structure

Every subframe presents the same structure. It is assumed that the first two OFDM symbols in each subframe are occupied by control channels. Besides, overhead due to transmission of reference signals has been considered. The remaining resources are filled with useful data.

B. Channel model

Data transmission and channel effect has been modeled in time domain. Received signal is obtained as a linear combination of the transmitted samples filtered with the channel response plus white gaussian noise.

The time-varying multipath channel is modeled in the link level simulator whose impulse response is:

$$h(t,\tau) = \sum_{l=1}^{L} h_l(t)\delta(t - t_l), \qquad (2)$$

where $h_l(t)$ and t_l are the complex value and delay of the time-varying multipath components, respectively. Concerning the values of $h(t,\tau)$, two wideband tapped delay-line profiles defined by 3GPP are employed in the simulations: Extended Pedestrian A (EPA) and Extended Vehicular A models (EVA) [11]. The first model shows lower frequency variability than the latter. Concerning time variation, it is assumed that the channel changed sample by sample (fast fading assumption), while in other papers it remains unchanged during the OFDM symbols or LTE subframes (slow fading assumption). This accurate modeling is necessary to account for inter carrier interference (ICI) produced in OFDM systems with time-varying channels. ICI can degrade the performance of FDE methods, such as those employed in this paper. Thus, it is necessary to accomplish such an exhaustive performance study.

Additionally, the correlation among channels has a severe impact on MIMO performance. In the link level simulator, matrices representing correlation among antennas are separately defined for the transmitter and the receiver according to [11]. Channel correlation matrix is obtained as the Kronecker product of the transmitter and receiver matrices. Next, this correlation is introduced in the simulations following the process described in [12].

C. Turbodecoding, Hybrid ARQ and MIMO

LTE specifications show clearly how data processing must be done in the transmitter. However, operation in the receiver is not specified. Thus, different receiver implementations are allowed and encouraged by 3GPP. In the link level simulator, classical solutions are adopted in the key processes at the receiver. A detailed description of the receiver features is provided in Table I. Although neither spatial multiplexing nor transmit diversity have been simulated, the conclusions of this assessment are also valid for these antenna configurations.

D. Transmitter impairments

Modulation inaccuracy at the transmitter is modeled through the introduction of a 6% Error Vector Magnitude [11].

TABLE I. MAIN SIMULATION PARAMETERS

Transmission BW	10 MHz (50 Resource Blocks)
Duplexing mode	FDD
FFT size	1024
OFDM symbols per subframe	14
CP length (samples)	72, first symbol of subframe 80, rest of symbols
Carrier frequency	2 GHz
Modulation and coding,Transport block size	QPSK 1/3, TBS=4.576 bits 16QAM 1/2, TBS=13.704 bits 64QAM3/4, TBS=30.882 bits
MIMO schemes	SIMO 1x2 (1trx, 2 rx) with MRC
Turbo-decoder	Max-log-MAP 8 iterations
HARQ with soft combining	6 processes, up to 3 retransmissions
Correlation among channels	low (uncorrelated)

Figure 2.   Effect of PDP estimation errors

Figure 3.   Effect of Doppler frequency estimation errors
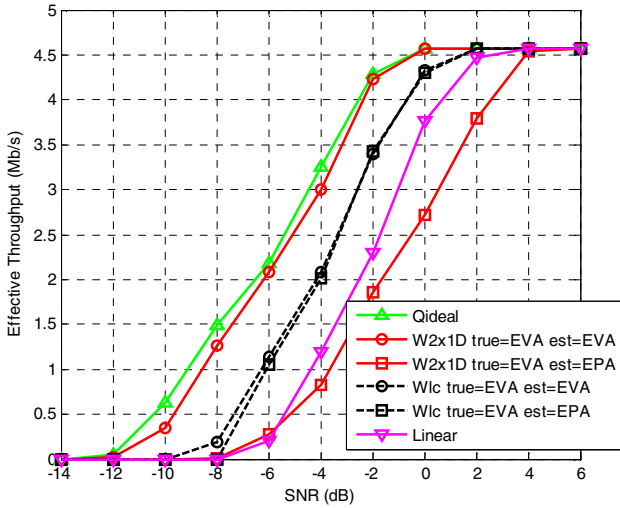
V.   RESULTS AND DISCUSSION

In this section simulation results are presented and discussed. Firstly, robustness of channel estimators is evaluated, highlighting the performance of the realistic estimator (Wlc method). Secondly, LTE system performance is presented employing the realistic channel estimator.

A. Evaluation of channel estimators robustness

Section III presented several pilot assisted channel estimation methods. Some of those methods assume that channel statistics are known 'a priori'. Those methods performing Wiener filtering in frequency domain assume a perfect knowledge of the frequency domain correlation (or equivalently, of the channel Power Delay Profile, PDP) and the noise power (ore equivalently, of the Signal to Noise Ratio, SNR), whereas those methods performing Wiener filtering in time domain assume the knowledge of the frequency domain correlation of the channel (or equivalently, of the Doppler frequency). Unfortunately, information about the channel statistics is not available at the receiver, although it can be estimated. Next, performance of channel estimators in presence of errors in the channel statistics estimation is presented.

First, it is evaluated how frequency domain correlation estimation error affects system performance. A number of performance curves have been obtained based on simulations conducted with EVA and EPA PDPs. Estimation error is emulated using the wrong frequency correlation function in the Wiener filtering. Doppler frequency has been fixed to 5Hz and modulation and coding was QPSK 1/3. In general, Qideal presents the best results while Linear is the worst one.

Concerning the simulations with EVA as the true channel, results in Fig. 2 show that, in absence of errors, W2x1D outperforms Wlc method. Nevertheless, PDP estimation error is highly harmful for the W2x1D but its effect on the system performance is negligible when using Wlc. For the sake of simplicity in Fig. 2 only the results for channel W2x1D and Wlc methods are presented but similar conclusion can be drawn comparing Wlc and WFD-LTD, although in absence of errors their performances are closer (1.5dB of difference).
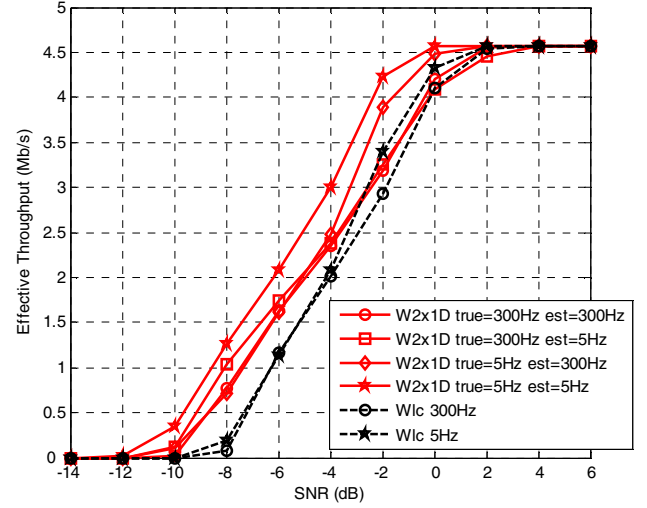
If the true channel is an EPA channel, results are similar to those of Fig. 2, although an important difference is observed: estimation error produces a negligible effect whatever the estimation method.

According to these results, it is concluded that full Wiener interpolation is more recommended in pedestrian scenarios, whereas in vehicular scenarios, more robust estimators as Wlc are preferred. Anyway, Wlc represents in general a good tradeoff between complexity and performance.

Another assumption in Wiener estimators is the knowledge of the time correlation function or the Doppler frequency (see (3)). Simulations have been carried out over EVA channels with two possible Doppler frequencies: 5Hz and 300Hz. Since the only method using time domain correlation information is W2x1D, errors have been only introduced in this estimator making calculations with a wrong Doppler frequency.

According to the obtained results, Qideal method is the best one, followed by W2x1D, WFD-LTD, Wlc and finally Linear. Therefore, the more information is used by the estimator, the better performance is achieved. For the sake of simplicity only the main results are shown in Fig.3. Wlc performance is not affected by Doppler estimation errors because not estimation is made. Conversely, W2x1D reduces its performance if the estimation is not accurate. Behavior of W2x1D is better than Wlc, but it is worth noting that perfect frequency estimation is assumed and that performance improvement comes at the cost of higher complexity.

The last assumption made by the Wiener estimators is the knowledge of the SNR. In order to assess the effect of this error, two kinds of curves have been obtained. First, it has been obtained error free performance curves, assuming that the real SNR is perfectly know. In the other kind of simulations, in order to emulate the SNR error, it has been assumed that the receiver uses a fixed SNR estimation. Three different values are used as constant estimations, representing low, medium and high SNR values. Since LTE SNR operating range is from -14dB to 26dB, low SNR value is defined as -7.33dB, medium SNR as 6dB and high SNR as 19.33dB.
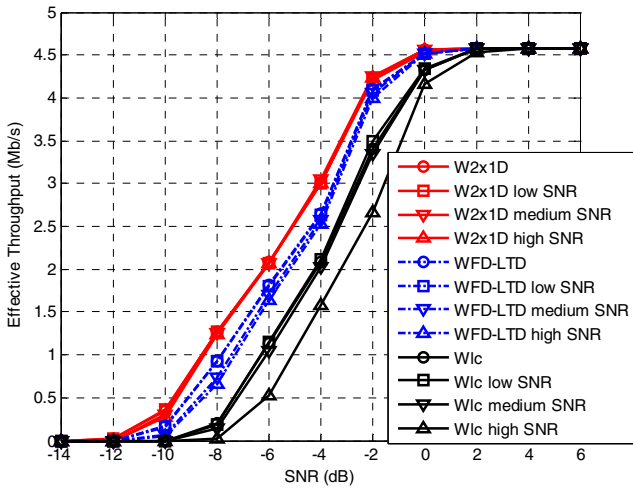
Figure 4.   Effect of SNR estimation errors

Figure 5.   LTE throughput for a EVA channel with Doppler frequency 5Hz

Fig. 4 shows the performance of W2x1D, WFD-LTD and Wlc estimators, i.e., those using SNR estimation. SNR estimation error produces a negligible effect on W2x1D performance, and the effect is small for WFD-LTD. Conversely, if the Wlc estimation is used, the high SNR assumption has an important impact on system performance. Nevertheless, this is the worst case, not expected in a real deployment, and a fixed medium SNR assumption would be enough to obtain a robust behavior.

B. LTE performance evaluation

In order to reduce receiver complexity and memory requirements and given that previous results demonstrate its robustness, the Wlc estimator is a firm candidate to be implemented in real LTE equipments. Results shown in Fig. 5 are an example of the realistic LTE performance using Wlc. In this example the full LTE SNR dynamic margin is covered and concerning the channel, EVA PDP and 5Hz Doppler frequency have been used. Note that the maximum system throughput is around 30Mb/s because neither the maximum code rate nor spatial multiplexing is taken into account. If that was the case, then this throughput would be increased.

VI.   CONCLUSIONS

In this paper a complete LTE Release 8 link level simulator has been presented together with several performance results. Specifically, some channel estimators of different level of complexity have been compared, assessing their behavior in realistic scenarios where the receiver lacks a perfect knowledge of channel statistics. It has been demonstrated that the performance of Wiener-based estimators can be hardly affected by failures on the frequency and time correlation function estimation. These failures and the need of reducing the receiver complexity have motivated the design of a simpler and more robust channel estimator. This estimator uses only the six nearest pilot symbols to apply a Wiener filter in frequency and, afterwards, a simple linear interpolation. The good performance of this estimator and, most of all, the fact that it withstands failures in frequency estimation, support the relevance of this proposal.
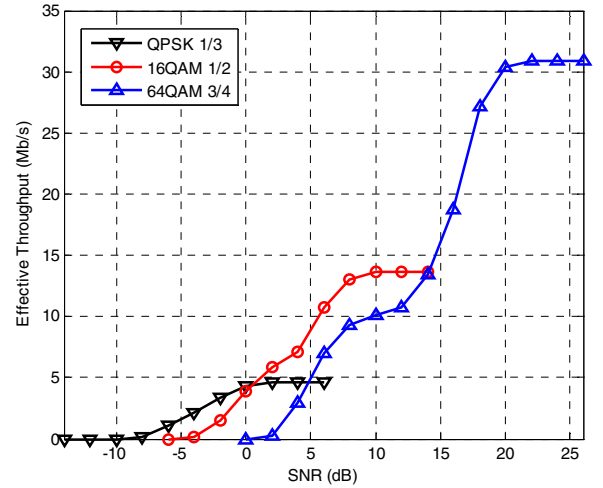
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Radio Spectrum Allocation in LTE: Different Alternatives for a Flexible Technology

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Abstract

This article discusses the implications of the different spectrum allocation schemes of 3GPP Long Term Evolution (LTE). Both frequency band and channel bandwidth can be adapted according to the standard but always under the constraints of the global spectrum regulatory framework, which is described in detail. Moreover, this article explains the effect of both factors on network deployment and capacity and performs a simplified deployment cost analysis in a specific scenario. In order to draw reliable conclusions, this paper presents several outcomes obtained from two complete system level and link level simulators, fully compliant with the specifications. Performance results show that the frequency band has a great impact on both system capacity and deployment cost, being up to 117% more expensive depending on the band. Concerning transmission bandwidth, spectral efficiency can be improved up to 47% by using wider bands. Therefore, excessive spectrum fragmentation should be avoided whenever possible.

Introduction

Social and economical aspects control the development of the mobile communications business, like other economic sectors. Consumer demand boosts all the technological advances, operators' capital investments and the amendment of the laws required to ensure the advance of the knowledge society towards the improvement of the quality of life of the citizens.

The mobile communications sector is characterized by a worldwide rapid increase in the number of users. According to the International Telecommunication Union[1] (ITU), in the last five years the number of worldwide subscribers has grown from 1.2 billion to more than 3.3 billion (49.42% of the world population), which implies growing at a Compound Annual Growth Rate (CAGR) of 23.3%. Even though these numbers are quite significant, it is worth noting that, in terms of the number of subscribers, the mobile communications sector has reached saturation point in a wide number of markets. In the European Union, mobile penetration rate is over 110%, whereas in developed Asian countries has reached 80%, just like in United States and Eastern Europe where the growth of mobile services has been quite important in the last years. Although there is still room for the potential mid-term growth of less-developed markets, operators in saturated markets need to foster the demand of new services to guarantee the future increase in their revenues. Consequently, in the years to come the mobile communications sector will be forced to increase Average Revenue Per User (ARPU) levels.

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[1] ITU World Telecommunication/ICT Indicators Database

That is why the scope of the mobile communications sector, also stated by ITU [1], is today more than ever to put on the market a new set of telecommunication services through the mobile phones. Among these services mobile TV, video on demand, interactive games and high quality music are expected to ensure a sharp upturn in usage of mobile services and consequent revenues.

With the aim of identifying the regulatory requirements of the sector, both the European Union and the UMTS Forum ordered market studies to foresee the future service demand and the traffic generated by this new demand. These studies are Future Mobile Services [2] and Magic Mobile Future 2010-2020 [3] respectively, whose market projections were based on the popularization of the abovementioned services and in the current upward trend of the market. Both studies predict a great rising in the traffic generated by mobile users until 2020, being the current mobile communication systems incapable of managing such increase.

3GPP Long Term Evolution (LTE) is the name given to the new standard developed by 3GPP to cope with these future market requirements. Therefore, LTE is the next step in the evolution of 2G and 3G systems and also in the provisioning of levels of quality similar to those of current wired networks. Due to the advantages offered by the Orthogonal Frequency Division Multiplexing (OFDM) technique, LTE can offer higher spectral efficiency than previous 3GPP technologies. This great improvement of throughput will likely transform the mobile business model and the mobile user behavior.

A key feature of LTE is its high spectral flexibility. LTE can be deployed in scalable bandwidths ranging from 1.25 MHz up to 20 MHz and in all frequency bands designated by ITU for International Mobile Telecommunications (IMT) [4]. This feature and the system performance targets defined by the standard [5] give operators considerable flexibility in their future technical and business strategies. Moreover, the capability of changing the working bandwidth of LTE allows operators to deploy this technology in any of their already-available frequency bands. This migration of less efficient technologies to LTE, also referred to as re-farming, will permit addressing future traffic demands. This fact is drawing the attention of not only those operators following the 3GPP specifications but also of other operators that have already expressed their interest in LTE as an evolutionary good option to reduce their expenditures thanks to the economies of scale.

This paper addresses the study of the different radio spectrum allocation alternatives for LTE. Both the choice of the frequency band and the allocated bandwidth have severe consequences in terms of spectral efficiency and coverage, which at the end directly affects the deployment cost and the quality of service offered to the end user. The results shown in this paper can be interesting for operators and spectrum regulation authorities in order to define proper strategies to increase revenues and boost the telecommunications sector.

Global Spectrum Regulatory Framework

The radio spectrum is a scarce resource that has a considerable economic and social impact. Albeit in the last analysis the governments of every nation are who decide on the spectrum allocation, the global coordination of the spectrum usage is under the responsibility of the ITU, which, concerning spectrum regulation, aims at facilitating the global roaming and decreasing

equipment cost by means of global economies of scale. Since 1992, and in the framework of the ITU-R (Radio Sector), United Nations have come to quite significant agreements at a global level to designate some specific frequency bands to a set of standards known as IMT, which covers IMT-2000, including future improvement of IMT-2000, and IMT-Advanced. 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 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 designated for IMT. With the aim of coordinating the global use of spectrum, every three to four years ITU-R holds the World Radiocommunication Conference (WRC), where ITU Radio Regulations (RR) governing spectrum distribution are adapted.

In 2003 ITU-R approved the Recommendation M.1645 [6], in which the objectives of the future development of IMT family were defined: to reach 100 Mb/s for mobile access and up to 1 Gb/s for nomadic wireless access with 20 MHz bandwidth. Despite LTE is not intended to achieve such objectives, 3GPP roadmap establishes that future evolution of LTE (called LTE-Advanced) will comply with the likely requirements of IMT-Advanced. Since Recommendation M.1645 states that these systems will be developed around 2010, ITU-R has already started the spectrum regulation tasks concerning IMT-Advanced. The first step was performing an in-depth study of the mobile market forecast and the development of spectrum requirements for the increasing service demand. Report M.2078 [7] predicted the total spectrum bandwidth requirements for mobile communication systems in the year 2020 to be 1280 MHz and 1720 MHz for low and high user demand scenarios, respectively. Bearing in mind that the spectrum bandwidth designed by ITU for IMT was much lower than this forecast (693 MHz in Region 1 - Europe, MEA, Russia -, 723 MHz in Region 2 -Americas - and 749 MHz in Region 3 - Asia, Oceania), and given that the time elapsed since the adaptation of the RR until the definitive allocation of a frequency band to operators takes from 5 to 10 years, the WRC-07 that took place in Geneva ended with the identification of new frequency bands for IMT technologies.

Figure 1 depicts the current state of the frequency bands reserved for IMT. Despite not fully corresponding to what was targeted, the new spectrum allocated for mobile communications will allow operators to face the initial development of technologies towards IMT-Advanced. Furthermore, as shown in the figure, the increasing demand for mobile services has been progressively recognized with additional spectrum, trend that is expected to be maintained in future WRCs.

As the predecessor technology to IMT-Advanced, LTE was designed to be rolled out in any of the frequency bands allocated for IMT [4]. Therefore, it is expected that next updates of the standard will also add the latest bands identified at WRC-07. In fact, some vendors have already announced that their first commercial releases of LTE will include them.
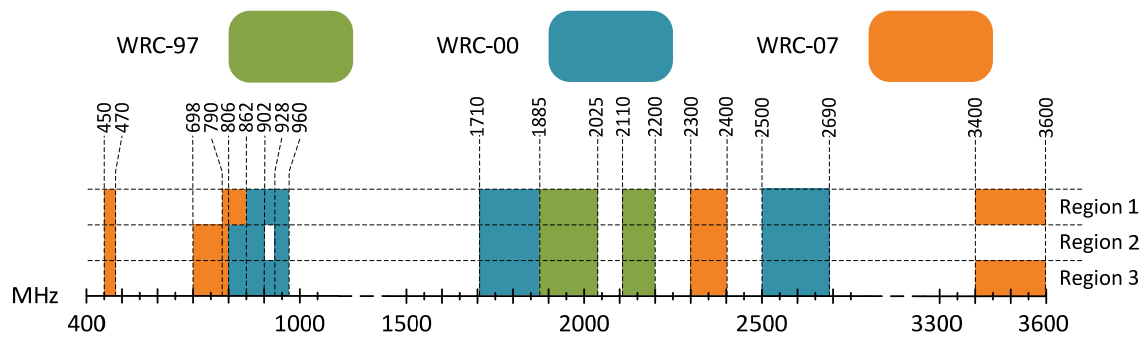
Figure 1. *Mobile frequency bands allocated for IMT technologies*

Analysis of Different Frequency Bands

As mentioned before, LTE can be deployed in several frequency bands. There are a number of factors to consider when determining the best band including technical, economical and even political aspects. This section assesses the performance of LTE in the five most likely LTE spectrum bands: 450 MHz band, Digital Dividend (DD) band around 700 MHz, Advanced Wireless Services (AWS) band between 1.7 - 2.1 GHz, 2.5 GHz band and the C band around 3.5 GHz. This study is performed from three different technical points of view: the receiver efficiency, system capacity and system coverage. The coverage study is completed with a simplified high level financial analysis of the LTE deployment at the different frequency bands from the perspective of an individual mobile operator. Results from these analyses constitute a guide to make an optimal frequency band decision.

It is appropriate to clarify that this section focuses on an early deployment scenario of LTE, accounting for the first three years of the mobile network, when the main goal is to maximize the coverage area. The coverage requirements can be calculated from the user throughput requirements defined in the specifications [5], being 0.2 b/s/Hz the target for the 5th percentile of the cumulative distribution function (CDF) of the spectral efficiency for 120 km/h.

Full bandwidth spectral efficiency and coverage

Firstly, the spectral efficiency of the LTE system as a function of the experienced signal to noise plus interference ratio (SNIR) has been obtained for each band using the full bandwidth, 20 MHz. With this aim, a number of simulations were conducted over a fully compliant LTE Release 8 link level simulator. According to the LTE system requirements, a speed of 120 km/h was assumed for system users. Full bandwidth transmission to a single user, SIMO 1x2 with MRC receiver, realistic channel estimation, adaptive modulation and coding (with the most efficient mode being 64QAM 3/4), hybrid ARQ with 4 retransmissions and Extended Typical Urban channel model were some of the main characteristics of the simulations. Concerning the frame structure, it was assumed the transmission of 11.5 OFDM data symbols per sub-frame. Refer to [8] for further information about the simulation assumptions.

Results have no significant differences in spectral efficiency among bands. Similarity of these values is due to the good performance of the channel estimator in this specific Doppler frequency range. Besides, for all bands Doppler shift is much less than subcarrier spacing (15 kHz) and the influence of inter-carrier-interference is almost negligible.
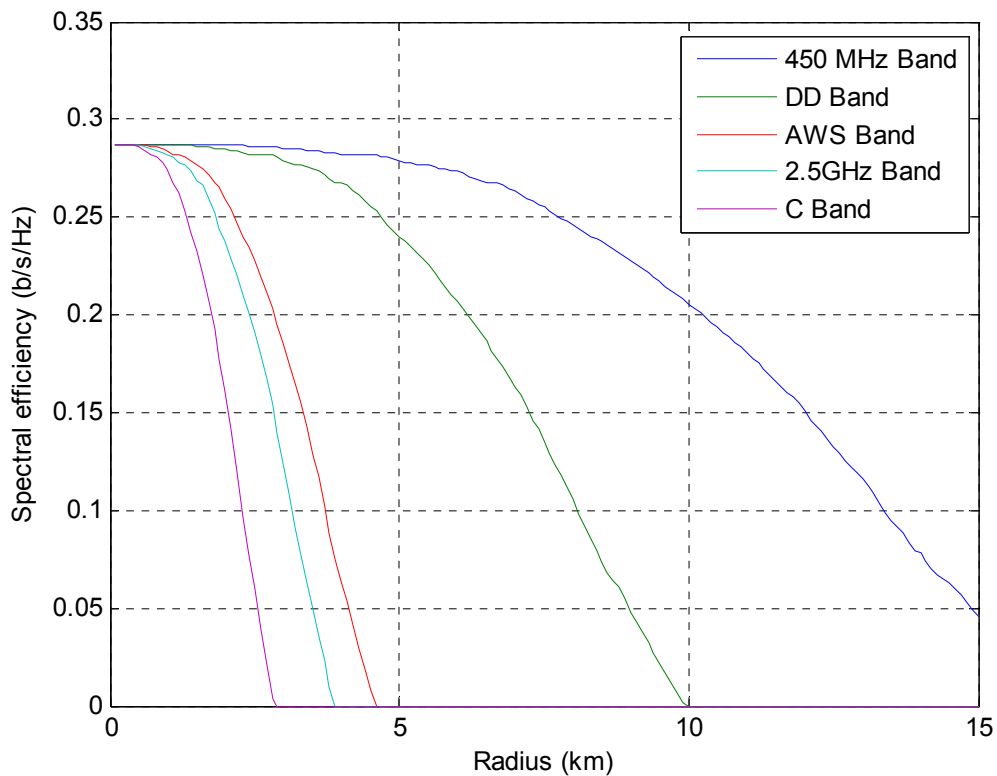
Figure 2. *5th percentile spectral efficiency vs. cell radius for different frequency bands*

Next, 5th percentile minimum spectral efficiency defined in the specifications was used to calculate the maximum cellular radius for each band. System level simulations with a full buffered user were carried out in an urban environment and a synthetic hexagonal scenario with 3 sectors per site and a reuse factor 1/3 (see next section for further details of system level simulations). Simulations with increasing cellular radii were conducted for each band obtaining the 5th percentile of the CDF of the spectral efficiency. These results are shown in Figure 2. Given the minimum spectral efficiency of 0.2 b/s/Hz, maximum cell radii result to be 10.23 km, 6.16 km, 2.85 km, 2.4 km and 1.72 km for the 450 MHz, DD, AWS, 2.5 GHz and C bands, respectively.

While spectral efficiency vs. SNIR was found to be almost frequency band independent, maximum radius for coverage requirements varies significantly depending on the frequency band. This dependency is basically due to the different path losses experienced in the mobile channel for each frequency (path loss increases with frequency), which produces a different SNIR distribution at the cell and, hence, a different spectral efficiency distribution.

Impact on capacity

Assuming the same deployment, i.e. considering the same cell radius, this section investigates which is the impact of frequency band choice on system capacity. Again, system level simulations were conducted in the above-mentioned scenario to obtain cell throughput. The considered cell radius was the minor radius from the previously obtained set, that is, 1.72km. This way, capacity was calculated under the same conditions for all bands.
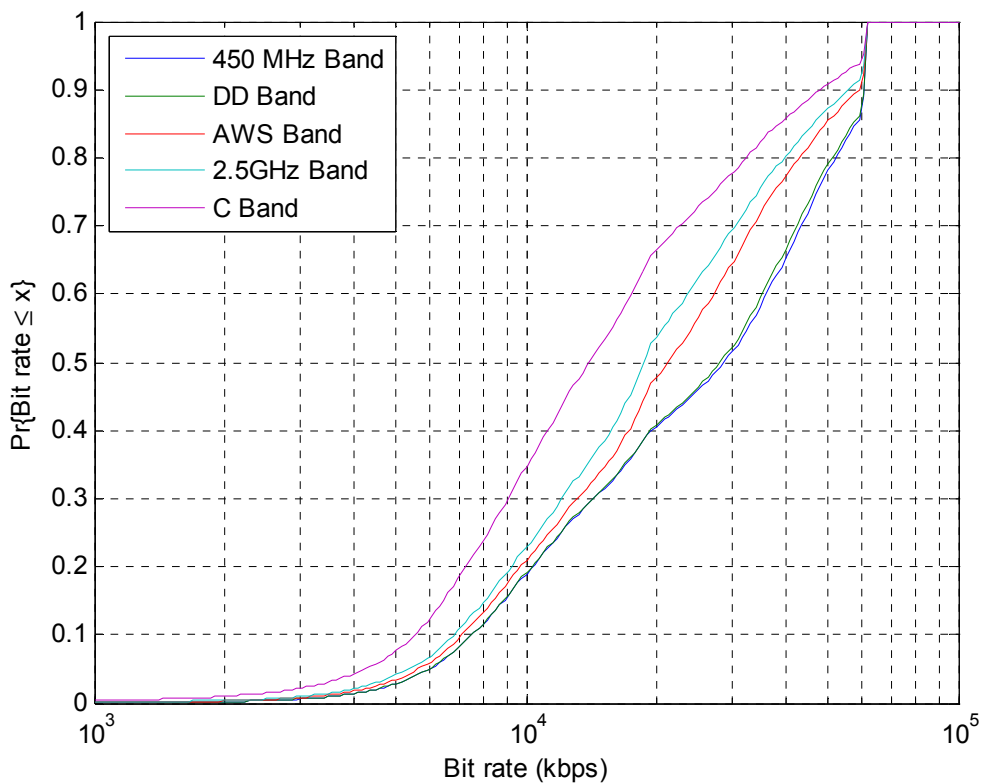
Figure 3. *Cell throughput CDFs for each frequency band*

Results of these simulations are summarized in Figure 3, which shows the cumulative probability density function (CDF) of cell throughput for each frequency band. Note that the maximum system throughput is around 60Mb/s because MIMO was not taken into account.

According to the throughput distribution, capacity decreases as frequency grows. Capacity reduction is almost inappreciable between 450 MHz and DD band, but cannot be neglected for the rest of bands. For example, the median throughput is 28.51 Mb/s for 450 MHz, 27.86 Mb/s for DD band, 21.14 for AWS band, 18.83Mb/s for 2.5 GHz band and 13.96 Mb/s for C band. It is worth highlighting that capacity reduction is of 26%, 34% and 51% for the latter three bands, which is a significant amount.

Economic impact on deployment cost

A simplified high level financial analysis of the LTE deployment was performed based on previous results. This study was carried out for a fictive region of an area of 65000 square kilometers similar to that described in [9], which represents a typical European country scenario. Although the total population was assumed to be 45 million people, the LTE network was expected to cover only 50% of the population. In particular, according to [9], the number of LTE subscribers served by one operator in this fictive scenario was predicted to be around 5 million by the third year. The migration of subscribers to the new network was supposed to occur in progressive stages during these three years.

For the financial analysis, Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) were calculated. In the CAPEX analysis it was assumed that the mobile operator deploys LTE

using the available infrastructure. Therefore, civil work expenditures were not taken into account, neither the cost of acquiring spectrum licenses, since operators may use frequency bands of current technologies to minimize the cost of LTE. Finally, CAPEX encompasses LTE equipment cost (50k€ per site [10]), labor-related deployment cost (10k€ per site) and upgrading the existing backhaul (2k€ per site). The number of sites multiplied by the investment cost per site yields the overall operator network investments. By combining the coverage area and the base station range, previously calculated, it is easy to obtain how many base stations are required.

On the other hand, OPEX accounts for site rental (10k€ per site per year [10]), data backhaul costs (5k€ per site [10]), maintenance (3k€ per site [10]), marketing cost (1.85 € per person [9]), administrative costs (addition of 10% of other running costs [9]) and the subsidy paid by the operator to reduce the price of new mobile terminals, thus facilitating the migration of subscribers (160€ per subscriber [9]). Similarly, OPEX was calculated multiplying the number of sites by the running cost per site plus terminal subsidies.

In addition to the CAPEX and OPEX analysis, financial studies usually comprise the estimation of the minimum ARPU levels necessary to ensure an overall payback period lower than 3 years. After performing the annuity analysis of a loan for CAPEX requirements over this 3 years period at rate of interest 6%, the minimum ARPU must cover the yearly installment plus OPEX.

Figure 4 shows the resulting deployment costs. The monthly ARPU needed to cover CAPEX plus OPEX in a LTE network varies between 9.96 and 21.7 €/month according to the simulations. Although both values are lower than the expected ARPU of 25 €/month for LTE services, these results demonstrate that the choice of the frequency band has a great impact on operators' expenditures.
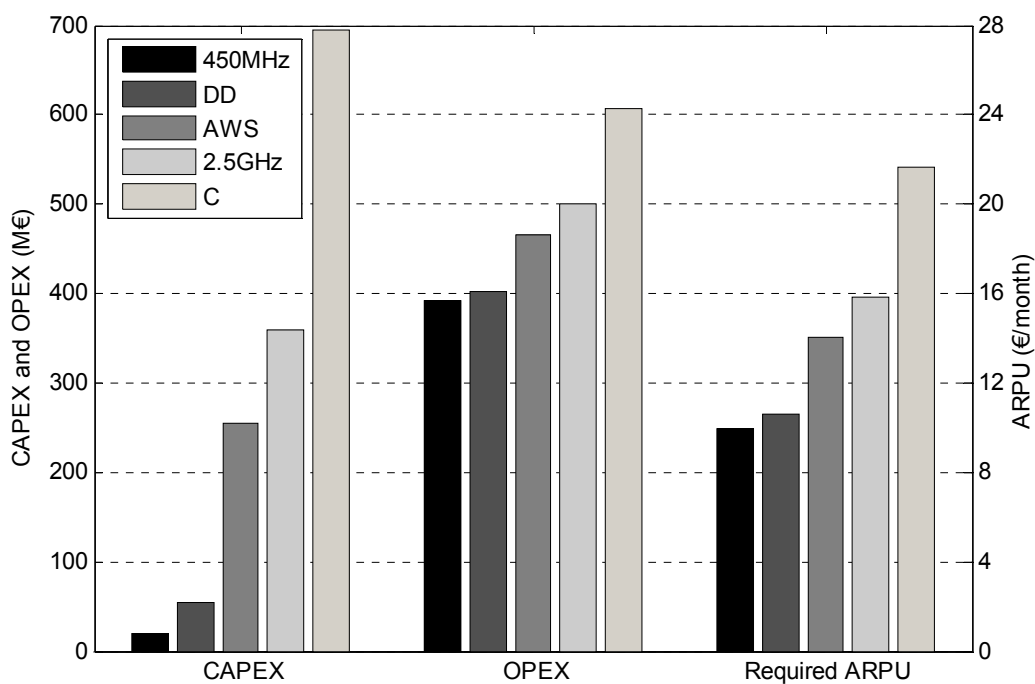

Figure 4. *Cost analysis of the LTE deployment*

In the lower bands CAPEX is considerably less than OPEX, most of all because the vast part of the deployment costs stems from the terminal subsidies. Conversely, in the upper bands CAPEX is even exceeding OPEX due to the increasing number of required sites. Furthermore, despite it is always preferable to allocate LTE in a lower band to reduce costs, the savings in expenditure are minimal between 450 MHZ and DD bands.

Finally, note that the higher deployment cost in the C band comes with 35 times extra capacity in comparison with 450 MHz band, due to the higher number of base stations installed in the network. However, this additional capacity could be underutilized since high capacity sites should be placed in hotspots according to the capacity demand and not to provide the necessary coverage.

Effect of Channel Bandwidth

Flexible Spectrum Use (FSU) provides a flexible way to adapt transmission capabilities to traffic variations. Several scenarios have been identified for this flexible bandwidth allocation, including hierarchical cell structures, relay networks and inter-operator frequency sharing. In fact, several options considering channel deployment of LTE femto-cells and macro-cells with one or several operators are under consideration. Thanks to the use of OFDM technique, LTE can adjust its bandwidth through a simple modification of the number of input symbols in the Inverse Fast Fourier Transform (IFFT) at the transmitter, which makes LTE technology suitable for FSU.

Concerning cellular relay networks, this concept has been identified as one of the most promising techniques to enhance coverage and capacity of LTE systems. One or several relays placed within the cell range retransmit part of the received information acting like a base station in the second hop. Obviously, available resources must be shared among the BS and all relays, being resources partitioned in both frequency and time domain, which varies the transmission bandwidth.

It is precisely the flexibility of LTE to transmit in scalable bandwidth what allows making the most of the available spectrum. Firstly, operators can consider the reuse of existing spectrum applying re-farming. Secondly, governments will be able to make a tailored spectrum allocation according to the needs and scopes of operators. Finally, operators will have the freedom to distribute the available spectrum among different carriers, relays or hierarchical cell structures according to their network design.

Whatever the FSU context, it is usually assumed that, given a specific bandwidth, the throughput is calculated by multiplying the spectral efficiency by the available bandwidth. Nevertheless, as shown in this paper, LTE performance depends on the employed bandwidth due to two effects: the different error correction capability of turbo coders and the multiuser diversity.

Additionally to the link level simulator explained in previous section, the results of this section were obtained with a dynamic system level simulator. The scenario consisted of 19 trisectorial cells with the cell under study in the center and two rings of interfering cells. The system was supposed to be saturated, thus, all the interfering cells transmitted at their maximum power, set to 0.4 W per 180 kHz wide resource block. Full buffered users were introduced in the

system, which were also mobile at a constant speed of 120 Km/h. Since each site comprised three sectors, all blocks, and thus the entire system bandwidth, were equally distributed among the sectors, what implies a frequency reuse factor 1/3. Moreover, time and frequency channel evolution was simulated for each link. The Hata model and its COST 231 extension were used to predict the median path loss.

System level and link level simulations were related through Look Up Tables (LUTs). Nevertheless, the LUTs calculation for Orthogonal Frequency-Division Multiple Access (OFDMA) is, in some way, more complex compared to traditional technologies. Firstly, because the effective throughput not only depends on the Transport Mode (TM), number of allocated blocks and channel SNIR, but also on how blocks are distributed in the frequency band. Secondly, because it is not possible to obtain an effective throughput per block, since the turbo coder works jointly over all of them. Generally, LUTs are 1-D indexed tables that give the effective throughput of the best TM for each SNIR level. However, for this study, LUTs were 2-D indexed tables that give the highest effective throughput value for each pair SNIR level - number of blocks. To this aim, the channel BLER was calculated through simulations separating the allocated blocks as much as possible inside the frequency band, thus, taking advantage of the spectral diversity.

The objective of this section is to compare the spectral efficiency for different bandwidth configurations (20 MHz, 10 MHz, 5 MHz, 3 MHz and 1.4 MHz) in the AWS band.
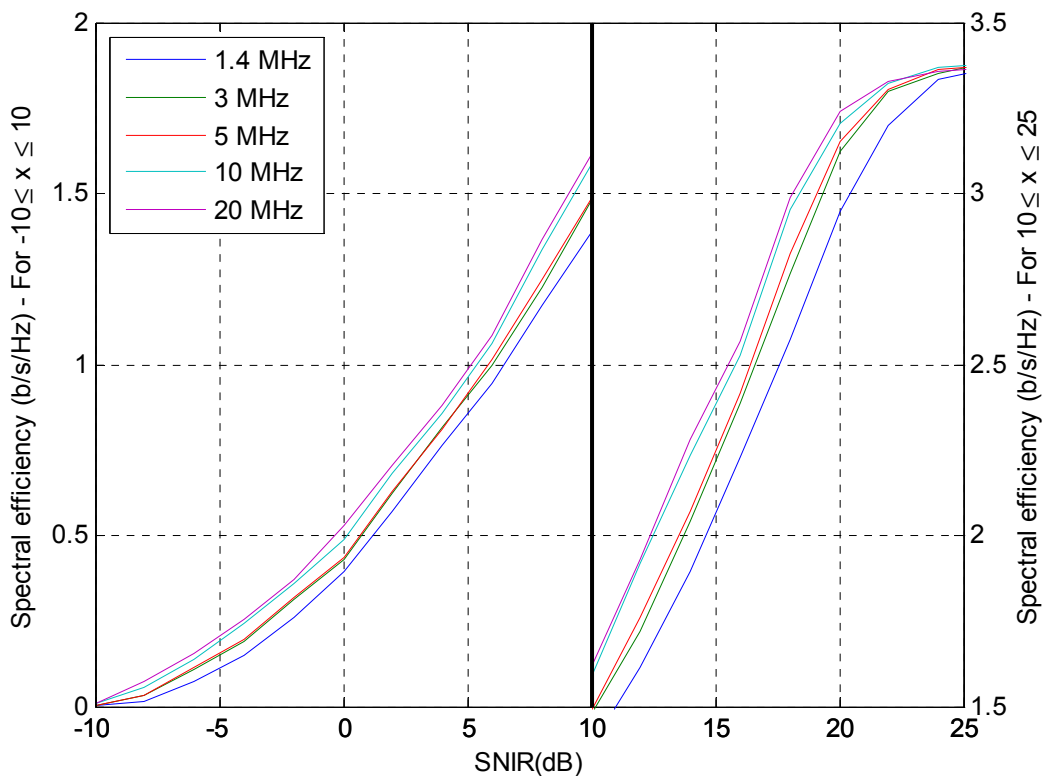

Figure 5. *Spectral efficiency of LTE for different bandwidth and transmitting 6 blocks*

Figure 5 shows the spectral efficiency obtained from a piece of LUT for the different configurations and the same number of allocated blocks (6 in this case). It is worth noting that the efficiency is higher for wider bands. This could be understood as a direct consequence of the spectral diversity, since better carriers can be selected with wider bands. Nevertheless, as explained before, the allocated blocks are always the same in the link level simulations, i.e. those that are separated as much as possible. Thus, this effect is not due to the good block selection that could be performed by a good scheduler. Consequently, the differences are caused by the turbo coder. Although it is equally likely to have a block with bad channel quality (low SNIR) in all the bandwidth configurations, it is more likely to have several blocks with bad channel qualities in the narrower bands. This makes the turbo coder correct more efficiently the errors in the wider bands and, thus, increase the spectral efficiency.

Finally, Figure 6 depicts the mean spectral efficiency versus the number of users in the system for the different bandwidths. All blocks are distributed among users following Proportional Fair (PF) policy. The PF policy takes into account the average bit rate perceived by each user obtaining a priority for each user and block. Higher priorities are given to those users with lower average bit rates and better channel qualities. Then blocks are allocated to the users with highest priority in each block. Results show that wider bands are again preferable in terms of spectral efficiency. However, there is a negligible difference between bandwidths higher or equal to 10 MHz. These bandwidths improve the spectral efficiency more than the 47% of the efficiency obtained with 1.4 MHz.
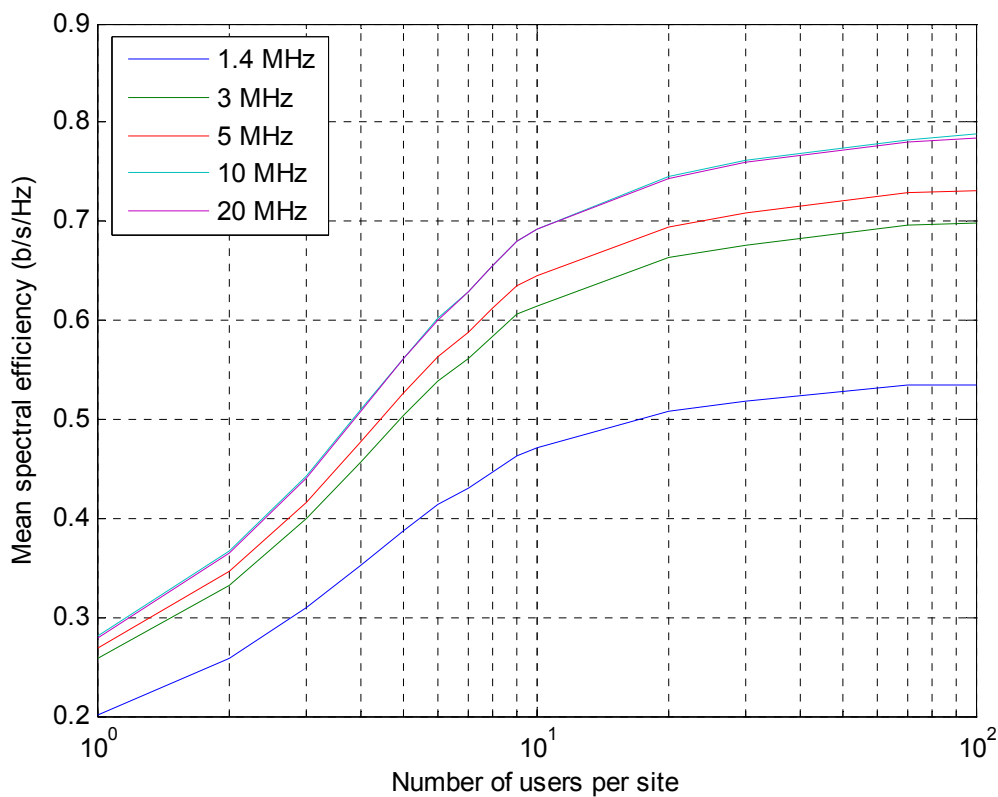

Figure 6. *Mean spectral efficiency with an increasing number of users in the cell*

Conclusions

LTE has been designed as a future technology to cope with next user requirements. One characteristic that facilitates its deployment is the high flexibility in frequency bands and bandwidths which allows LTE to be rolled out together with current technologies and even the re-farming towards LTE.

This article has shown how the band and bandwidth allocated to an operator affect the final performance. Concerning the frequency band allocation, lower bands are better for an initial deployment. Although channel estimation protects data from the effects of Doppler frequency, lower bands are preferable because of their longer range, which means lower investment for a first deployment based on coverage area. In this context, the necessary ARPU to cover CAPEX and OPEX in the DD and 450 MHz bands are similar and about 46% compared to the C band. Thus both bands are good candidates for a low cost LTE deployment. However, frequency band choice should also take into account high bandwidth demands that could not be satisfied in the lower bands due to restrictions in spectrum availability.

Concerning transmission bandwidth, wider bands are preferable. Bandwidths of 10 MHz or wider have very similar spectral efficiencies and, thus, spectrum should not be fragmented into pieces narrower than 10 MHz whenever possible.

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Performance Evaluation of 3GPP LTE:
The Need for an Accurate Link Level Calibration

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Abstract: The path towards IMT-Advanced has started in the ITU-R. The different IMT-Advanced proposals will be verified through the self-evaluation made by the proponents and a set of External Evaluation Groups. Coordination between evaluation groups is strongly recommended by ITU-R. Therefore, there is a need to define an accurate methodology for the calibration of the simulation tools used during this process. The scope of this paper is to present the complete link level calibration process methodology defined in the framework of the WINNER+ project, focussing on the key aspects of the LTE system. A detailed step-wise approach to execute the calibration of the link level simulator is provided. The methodology is based on breaking down the entire simulation chain into its single building blocks, identifying basic subsets of functionalities that can be assessed independently. Particular attention is given to provide valuable references from 3GPP documentation, strengthening and validating the overall process.

Keywords: LTE; calibration; link level simulation; IMT-Advanced

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1. Introduction

ITU-R is defining a new global framework for international mobile telecommunications called IMT-Advanced, providing a reference for the development of the fourth generation of mobile communication systems (4G). The Recommendation M.1645 [1] specifies the objectives of the future development of the IMT-Advanced family: among them is to reach 100 Mbps for mobile access and up to 1 Gbps for nomadic wireless access. ITU-R issued a Circular Letter [2] calling for candidate Radio Access Technologies (RATs) for IMT-Advanced. It is foreseen that several technologies will be sent to the ITU-R for their study and approval inside this framework. Among those technologies it is pertinent to highlight the candidate of the 3GPP, Long Term Evolution (LTE)-Advanced, due to its support from most of the worldwide mobile broadband organisations.

The 3GPP divided the evolution towards 4G into two phases: the former concerns the completion of the first LTE standard (Release 8 and Release 9), whereas the latter intends to adapt LTE to the requirements of 4G through the specification of a new technology called LTE-Advanced (Release 10). Following this plan, in December 2008 3GPP approved the specifications of LTE Release 8. The LTE-Advanced Study Item was launched in May 2008, in order to analyse the likely evolution of LTE based on a new set of requirements, expecting its completion in October 2009 according to the ITU-R schedule for the IMT-Advanced process.

The assessment of the different IMT-Advanced proposals, LTE-Advanced included, will be made through cross checking the reports prepared by a set of External Evaluation Groups (EEGs) and the self-evaluation made by the proponents. Currently (April 2009), there are twelve registered EEGs. Among these, there is a special interest in the results of the evaluation fulfilled within the European project WINNER+ [3].

Coordination between evaluation groups is strongly recommended by ITU-R to facilitate comparison and consistency of results and to simplify the understanding of differences in evaluation results achieved by the independent evaluation groups. Indeed, the divergence in the results obtained in the evaluation of the same system is a common problem encountered in all forums where researchers coming from different bodies try to provide their contributions to the progress of science and technology [4]. A possibility to overcome this situation is the comparison of different approaches using the same calibration process and benchmark data. In this framework, and in order to simplify the IMT-Advanced assessment, ITU-R has already approved a number of documents describing the evaluation process, requirements and evaluation criteria. In particular, Report M.2135 [5] contains the

detailed simulation assumptions and the evaluation methodologies of IMT-Advanced. This document represents a significant calibration effort that intends to ensure the proper harmonisation of the tools used by the EEGs for performance evaluation of the IMT-Advanced technologies.

Despite this calibration work, Report M.2135 is mainly focused on the definition of the reference scenarios for system level simulations. Concerning link level simulations, only channel models and reference speeds are provided. Actually, although ITU-R states that, for the sake of having a good comparability of the evaluation results, link level simulation methodologies must be unified, there is not any indication about link level calibration procedures and link-to-system level interface definition. Moreover, it is to be considered that 4G and future Mobile Broadband Networks adopt radio access techniques that require the configuration of a number of different parameters, as compared with currently deployed systems. This is a direct consequence of the implementation of technical features that were not present in previous systems, mainly related to the usage of the Orthogonal Frequency-Division Multiple Access (OFDMA) scheme. As a result, the study of these networks requires the introduction of many new concepts and the definition of much more complex evaluation scenarios than in the past. Most of all, link-to-system modelling must be specially adapted to the new radio link [6].

1.1 Scope of this work

In order to fill the link level calibration gap, the WINNER+ project has set up an internal activity for the definition of an accurate harmonisation procedure. The intention of this action is to share the experience, information and benchmark data with the remaining EEGs in order to foster the required coordination and unification of results.

The scope of this paper is to present the complete link level calibration process methodology defined in the framework of WINNER+, starting from the OFDM testing up to the link-to-system modelling. Since 3GPP LTE is precursory of LTE-Advanced, this paper is focused on the LTE technology. Besides, the resulting process of calibration described in this paper is partially based on the experience of evaluation of LTE performance inside the 3GPP, and is totally aligned with their conclusion, which validates the overall process.

Actually, several papers deal with the performance evaluation of LTE in FDD mode. However, up to date this assessment has been partially done because of the following reasons. First, some of these works only focused on the physical layer, leaving out the

retransmission processes and error correction [7]-[9]. System level analysis need 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 [10]-[11]. Finally, other works including the complete transmission chain assume an interference free environment and do not provide the information required by system level simulators [12]. Therefore, this paper presents a method to evaluate LTE radio performance considering a transmission chain fully compliant with LTE Release 8 and including realistic HARQ (Hybrid ARQ) and turbo-decoding. Besides, a proper link-to-system modelling is also described, which completes the analysis of all the tools that are needed for an accurate system level evaluation.

2. Evaluation of Next Generation Networks

2.1 Basic Process of Assessment

Given the enormous complexity of current and future wireless systems, it is impossible to evaluate their performance using analytical methods. For this reason, system modelling and computer simulation represent a good alternative for the assessment of these systems, achieving a good trade-off between complexity, cost, time of development and accuracy.

A possible focus for the simulation of a wireless system would be to consider a global model of the network that emulated the interaction between a number of base stations and mobile terminals. This simulation would take traffic aspects into account together with the users' mobility while reproducing, at the same time, channel coding, modulation and propagation aspects associated to each one of the wireless links. However, such a complete simulation model would suppose a prohibitive computational burden. In order to reduce such complexity, simulation is usually divided into two stages or levels of abstraction known as link level and system level.

Link level simulations are used to assess the performance of the physical layer plus those MAC aspects directly related to the radio interface, such as the Hybrid ARQ mechanisms. At the link level a continuous radio link is modelled, including in the simulation specific features like synchronisation, modulation, channel coding, channel fading, channel estimation, demodulation, etc. The main results of these simulations allow characterising

the user Quality of Service – measured in terms of either Bit Error Rate (BER) or Block Error Rate (BLER) – as a function of the Signal to Noise plus Interference Ratio (SNIR). On the other hand, system level simulations allow evaluating the performance of the global network. At this level, system modelling encompasses a set of base stations and all their associated user terminals. The signal level received by each user, as well as other users' interferences, is modelled taking into account the propagation losses and channel fading effects. Besides, in dynamic system level simulators users' mobility and traffic generation is also included together with all Radio Resource Management (RRM) operations, such as link adaptation, dynamic resource allocation, handovers, etc. SNIR is calculated for each active user taking into account the current configuration of the network. These SNIR values can be then translated to BER or BLER values using the results obtained in the link level simulations. This interaction between link and system level simulators is usually referred to as Link to System (L2S) interface. Note that, as aforementioned, both levels of simulation are evaluated independently.

2.2 Relevance of Link Level Simulations in the IMT-Advanced Evaluation

Four of the thirteen requirements and related evaluation methodologies specified by the ITU-R require the usage of simulation tools, whereas the remaining aspects are assessed either analytically or by simple inspection. Obviously, evaluations through simulations include both link and system level simulations. Concerning link level simulations, mobility requirements have been defined by the ITU-R in terms of link spectral efficiency in the uplink, i.e. link data rate divided by channel bandwidth. Therefore, this evaluation item will be checked by comparing the results of the link level simulation. Concerning the evaluations based on system level simulations, it is remarkable that not any system level simulation can be built without an accurate characterisation of the radio link.

The implementation of the link level simulator is comparatively much more arduous and difficult to draw out, since the whole transmission and reception chain of the system must be implemented. It entails, after all, designing a software prototype of the base station and the mobile terminal lower layers. In addition, the harmonisation process is certainly much more complicated at the link level. In spite of having a common channel model and an accurate description of the technology, several differences can be detected in the implementation of the receiver and, subsequently, in the system behaviour. Since the receiver design is not specified to foster competition among mobile manufacturers, it is quite important to define a reference receiver that allows replication of results. However,

the ITU-R has not directly tackled this problem, which adds complexity to the comparison process. This paper intends to fill this gap.

3. System Modelling

This paper describes the calibration process followed in WINNER+ project with regards to LTE link level simulations. Specifically, this section focuses on the description of those simulation details not undertaken in standards but essential for a proper calibration. With this aim, the key aspects of LTE modelling are explained. Special attention is paid to channel modelling, modulation, channel estimation, description of the reference receivers and channel coding. The last part of this section defines the key performance metrics used in link level simulations.

3.1 Channel Models

In the evaluation of the IMT-Advanced candidates, channel models are of paramount importance to guarantee an accurate modelling of the propagation conditions. The ITU-R has defined in [5] a channel model that can be parameterised to cover all the defined test environments. The proposed model belongs to the family of stochastic models based on the geometry and directions of the rays. Actually, the main features of this model are quite similar to the Extended Spatial Channel Model (SCME) defined by the WINNER project [15] and also described by the 3GPP [16]. According to [5] each transmitter and receiver pair comprises a set of clusters – propagation paths – each containing twenty different rays. Every ray is characterised by a set of parameters, such as angle of arrival, angle of departure, delay and relative power. Finally, the superposition of all these rays results in different correlations among the antenna elements and a geometry-dependent temporal fading.

Given the complexity of this model, the ITU-R has specified in [5] an alternative method based on the usage of a correlation matrix. This simpler channel model combines an environment-specific tapped delay line with Doppler spectrum, with the incorporation of a total covariance matrix per tap in case of Multiple Input Multiple Output (MIMO). Since the 3GPP has also suggested this model for the conformance specification of user equipments [17], this is the model chosen in WINNER+ for link level calibration issues.

To calculate the channel samples in a SISO channel, each tap is independently generated following the improved Jakes' methods with sum of sinusoids [18]. This method is

preferred due to its higher computational efficiency and good statistical characteristics of the generated sequences. The power delay profile information is extracted from [17]. For each tap and each time index, and assuming a $P \times Q$ antenna configuration, MIMO correlations are introduced with a linear transformation of the $P \cdot Q$ samples. This linear transformation is controlled by a shaping matrix calculated with the Cholesky factorisation of the MIMO covariance matrix. It is assumed that the covariance matrix is derived as a Kronecker product of the polarization covariance matrix and the correlation matrices calculated at the base stations and at the user equipment [19]. The correlation matrices are included in the 3GPP specifications [17] and remain constant for all the simulation duration.

3.2 Physical channels and modulation

Due to extremely high peak rate requirements imposed by the IMT-Advanced family of standards, wideband channels are mandatory – up to 100 MHz – and radio technologies capable of dealing with frequency-selective channels are required. OFDM modulation is specifically suited for broadband wireless systems. Moreover, OFDMA provides high MIMO spectral efficiency, makes the most of multi-user diversity and facilitates the flexible deployment in several frequency bands, as required by the ITU-R [5]. Therefore, it is foreseen that many of the candidate radio interface technologies will be based on OFDMA. In fact, OFDM and OFDMA have been chosen in the downlink of LTE and LTE-Advanced. Concerning the uplink a similar scheme called DFT-spread-OFDMA or Single Carrier FDMA (SC-FDMA) is used [20].

OFDM radio resources can be seen as a time-frequency grid where the minimum frequency resolution is the bandwidth of a subcarrier and the minimum resolution in time is the duration of an OFDM symbol. In LTE several combinations of subcarrier bandwidth are allowed: 15 KHz and 7.5 KHz. OFDM symbol duration depends upon the selected subcarrier bandwidth and the length of the cyclic prefix.

On the other hand, OFDMA is used as the multiple access technique. A Resource Block comprises 12 adjacent subcarriers in frequency domain and one 0.5 ms slot in time. The minimum schedulable unit is a group of two Resource Blocks contiguous in time (but possibly not in frequency). Frame structure is such that a frame lasts 10ms and is divided in 10 subframes each one formed by 2 slots [20].

3.3 Channel estimation

To be able to process the received symbols it is necessary to estimate the channel that exists between the user equipment and base station antennas or vice versa. Pilot symbols are inserted into the resource grid for that purpose. LTE specifications explain their generation and location in [20].

The quality and the complexity are two of the main parameters in the design of any channel estimator. In the calibration process one reference estimator must be chosen considering the trade-off between feasibility and simplicity. The selected estimator in downlink consists of, firstly, a Wiener filter in frequency that uses only the six nearest pilot symbols and, secondly, a linear interpolation in time.

In the frequency domain, the six estimated reference signals nearest to a given symbol are arranged in a vector p. The channel response $\tilde{H}_f(l)$ for a given time and for all subcarriers can be estimated by:

$$\tilde{H}_f(l) = \left[R_{pp} + \sigma_n^2 I \right]^{-1} R \Big]^* p,$$

where R_{pp} is the autocorrelation matrix of the actual channel response in the six reference signals – of size 6×6 –, R is the cross-correlation matrix between the channel response and the pilot symbols – of size 6×6 –, I is the identity matrix, σ_n^2 is the noise power and * represents the hermitian operation. The matrices R_{pp} and R are both calculated using the correlation functions of the channel. The frequency correlation is determined by applying the Fast Fourier Transform (FFT) to the power delay profile, whereas the time correlation fits the zero order Bessel function:

$$R_h(\tau) = J_0(2\pi \tau v / \lambda),$$

where v is receiver velocity, λ is the wave length and τ represents the delay. Despite the fact that Wiener interpolation requires *a priori* knowledge of the frequency and time correlation and the noise power, this method is quite robust, that is, it perfectly withstands errors in the estimation of these parameters. Therefore, this channel estimator can be considered an optimum estimator because it presents a good trade-off between complexity and performance.

In the time domain, four frequency estimates are available per subframe. Therefore, the intermediate channel estimates for each OFDM symbol are calculated through linear interpolation.

In the uplink, reference signals are transmitted only in those RB conveying data. This implies that the amount of channel information is lower than in the downlink. The channel estimation is suggested to be done using a Maximum a Posteriori (MAP) estimator, which is similar to the Maximum Likelihood (ML) method with one condition: noise power and covariance matrix must be known . The signal received by the base stations at pilot positions can be represented as:

$$Y = X \cdot H + N = X \cdot F \cdot h + N,$$

where X is a diagonal matrix containing the transmitted reference symbols − of size $J \times J$, being J the number of transmitted symbols −, H is the frequency response, N the noise power in the frequency domain − of size $J \times 1$−, F is the Fast Fourier Transform (FFT) matrix − of size $J \times J$ − and h is the impulse response in the time domain. F is defined as:

$$F = e^{j\frac{2\pi lk}{J}}, \quad l = k = 0, \cdots, J-1$$

The MAP algorithm obtains the impulse response using:

$$h = (B^* B + \sigma_n^2 \Lambda_h^{-1})^{-1} B^* Y,$$

where $B = X \cdot F$ and $\Lambda_h = E\left[h \cdot h^*\right]$ is the covariance matrix of the channel. The corresponding expression for the frequency response is:

$$H = F \cdot h.$$

Finally, the matrix F can be reduced to a size of $J \times L$, where L is the length of the channel impulse response. Moreover, if $L < J$, then $J − L$ noise values will have been eliminated − see dimensions of the received signal −. Therefore, the performance of this estimator increases when $J \gg L$. Note that with the MAP method it is also necessary to estimate the length of the channel.

3.4 Reference Receivers

With of the aim of increasing the system capacity, in the LTE specification MIMO configurations have been defined for downlink transmission, such as transmit diversity and spatial multiplexing [20]. Another option is considering only one transmit antenna, what is called single antenna transmission. This results in a Single Input Multiple Output (SIMO) configuration if more than one receive antenna is used. SIMO configuration is the only possibility in the uplink for the Release 8 of LTE. The antenna configurations in the link level simulation must strictly follow the standard. Besides, the optimum processing method

to be applied at the receiver depends upon each antenna configuration and must be explicitly stated to allow calibration. The scheme shown in Fig 1 is valid for all configurations in both downlink and uplink. In transmission, after multiplexing q codewords ($q = 1\ or\ 2$ in the downlink for spatial multiplexing and $q = 1$ in the uplink) in υ layers, the symbols are multiplied by a precoding matrix, T, of size $P \times \upsilon$, being P the number of transmit antennas. This matrix depends on the antenna configuration as specified in [20]. Therefore, the received symbols can be calculated as:

$$Y = H \cdot T \cdot X + N,$$

where H is the channel frequency response – of size $Q \times P$, being Q the number of antennas in reception –, X a vector of υ transmitted symbols and N an $Q \times 1$ vector of noise.

The above expression can be simplified by defining a new matrix $H' = H \cdot T$ of size $Q \times \nu$. This transformation results in a common definition of the received bits that only depends on the applied precoding matrix.
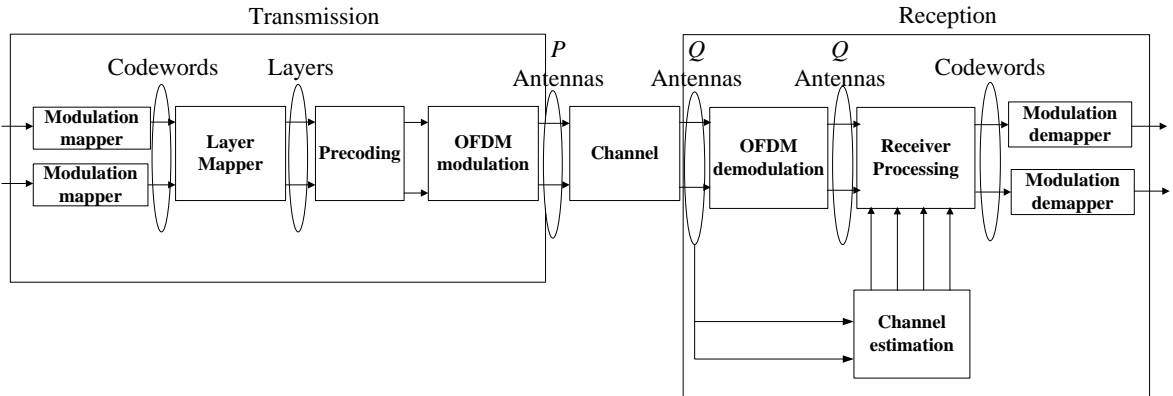
Figure 1. Transmission chain defined in LTE

To process the received symbols, two methods are suggested to be implemented for the calibration: Zero Forcing (ZF) and Minimum Mean Square Error (MMSE). For SIMO configurations, the ZF receiver is equivalent to the classic method of Maximal Ratio Combining (MRC). The symbols are equalized as:

$$\tilde{X} = RY = R(H'X + N) = RH'X + RN$$

In order to properly decode the transmitted symbols, the product RH' shall be ideally the identity matrix. Therefore, R is calculated using the Moore Penrose pseudo inverse, because matrix H' is not necessarily square. However, when the channel suffers a deep

fading the channel sample is low and, consequently, the result of the inverse has a high value. This implies a significant increase in the noise term *RN* that degrades the system performance. The second type of receiver based on the MMSE algorithm gives much better performance. In this case, the received data are equalized as:

$$\tilde{X} = (H'^{*}H' + \sigma_n^2 I)^{-1}H'^{*}Y = (H'^{*}H' + \sigma_n^2 I)^{-1}H'^{*}(H'X + N)$$
$$= T^{-1}(H'X + N) = T^{-1}H'X + T^{-1}N$$,

being I the identity matrix and σ_n^2 the noise power of the channel. Finally, it is important to highlight that both methods, i.e. ZF and MMSE, have an effect on the turbo decoding functioning because of the changes in the received SNIR. For that reason, the mapping from modulation symbols obtained after ZF or MMSE to the information required by the decoder must be properly configured.

3.5 Channel Coding

In LTE and LTE-Advanced, turbo coding has been selected as the FEC scheme for both the Physical Downlink Shared Channel (PDSCH) and the Physical Uplink Shared Channel (PUSCH). The LTE turbo coder is a Parallel Concatenated Convolutional Code (PCCC) with two 8-state constituent encoders equal to that of UMTS but with a new quadratic permutation polynomial QPP) internal interleaver. The coding chain is completely defined by the standard [22].

Nevertheless, receiver algorithms are not defined by the standard and hence different decoding alternatives can be followed. For calibration issues the classical log-MAP algorithm is suggested to be chosen [14][23]. This algorithm presents a good trade-off between complexity and performance, which justifies its common use in many link level simulators. In [23] several interesting implementation tips are provided to obtain an efficient solution and avoid overflow in calculations. Many references in the bibliography study turbo coding using low order modulations, like BPSK, and AWGN scenarios. However, LTE performance analysis requires the simulation of multipath scenarios and high order modulations. As a consequence, the calculation of the bit level LLR inputs used in the log-MAP algorithm must take into account the exact channel state and the specific modulation. A good description of this problem can be found in [24]. This work also provides a method for efficiently obtaining approximated LLR calculations.

Besides, in LTE the FEC operation is complemented with a Hybrid ARQ process. If decoding fails, the ARQ mechanism allows the retransmission of incorrectly received blocks. But, HARQ goes one step ahead since it allows combining the retransmitted blocks

to increase the probability of a correct decoding. Several options can be found concerning the implementation of the HARQ process (see, e.g., [25][26]). The chosen solution assumes that the combination is done before decoding, that is, bit level LLR inputs are calculated independently for each reception and accumulated in a soft buffer.

3.6 Performance Metrics

Computer tools enable to build a representation of the system by simulating its operation. Operating conditions are specified through system parameters. Running the simulation and measuring its outputs gives an insight into the performance of the whole system depending on the specified operating conditions. Once the basic key models of the LTE link level simulator have been defined and implemented, the next step to be fulfilled is to identify the proper metrics that can provide an indication of the performance of the system functionalities, depending on the specified operating conditions.

When referring to link level, performance is assessed by running Monte Carlo simulations and the typical indicators that are taken as a measure of the system performance are the following:

- Bit Error Rate (BER), representing the ratio of the number of bits incorrectly received to the total number of bits sent during a specified time interval, versus the correspondent value of SNIR. This BER can be measured at the MAC layer and, hence, includes the application of FEC and HARQ processes;

- Block Error Rate (BLER), representing the ratio of the number of Transport Blocks (TBs) incorrectly received to the total number of TBs sent during a specified time interval, versus the correspondent value of SNIR;

- Throughput, representing the average data rate that the single transmitter-receiver link is able to deliver, versus the correspondent value of SNIR;

- Relative Throughput, which normalises the throughput indicator dividing it by the maximum;

- Link spectral efficiency value, calculated as the throughput normalised by channel bandwidth.

As mentioned in Section 2, according to the particular Link to System interface, the SNIR value can be an effective one. It is interesting to notice that, within ITU-R specifications, different key performance indicators are suggested depending on the particular adopted simulator class [27]. In particular, for the class of link level simulators, performance is identified by means of the data rate at certain mobility classes.

The link level simulation results are mainly aimed to verify the performance of a single transmitter-receiver chain but are also useful to assess separately the different receiver algorithms, since many receiver functionalities are not standard-specific and their implementation is left to each vendor.

4. Calibration Process

This section describes in detail a step-wise approach to execute the calibration process for a LTE link level simulator. The methodology is based on breaking down the entire simulation chain of a link level simulator into its single building blocks, as shown in Fig 2.
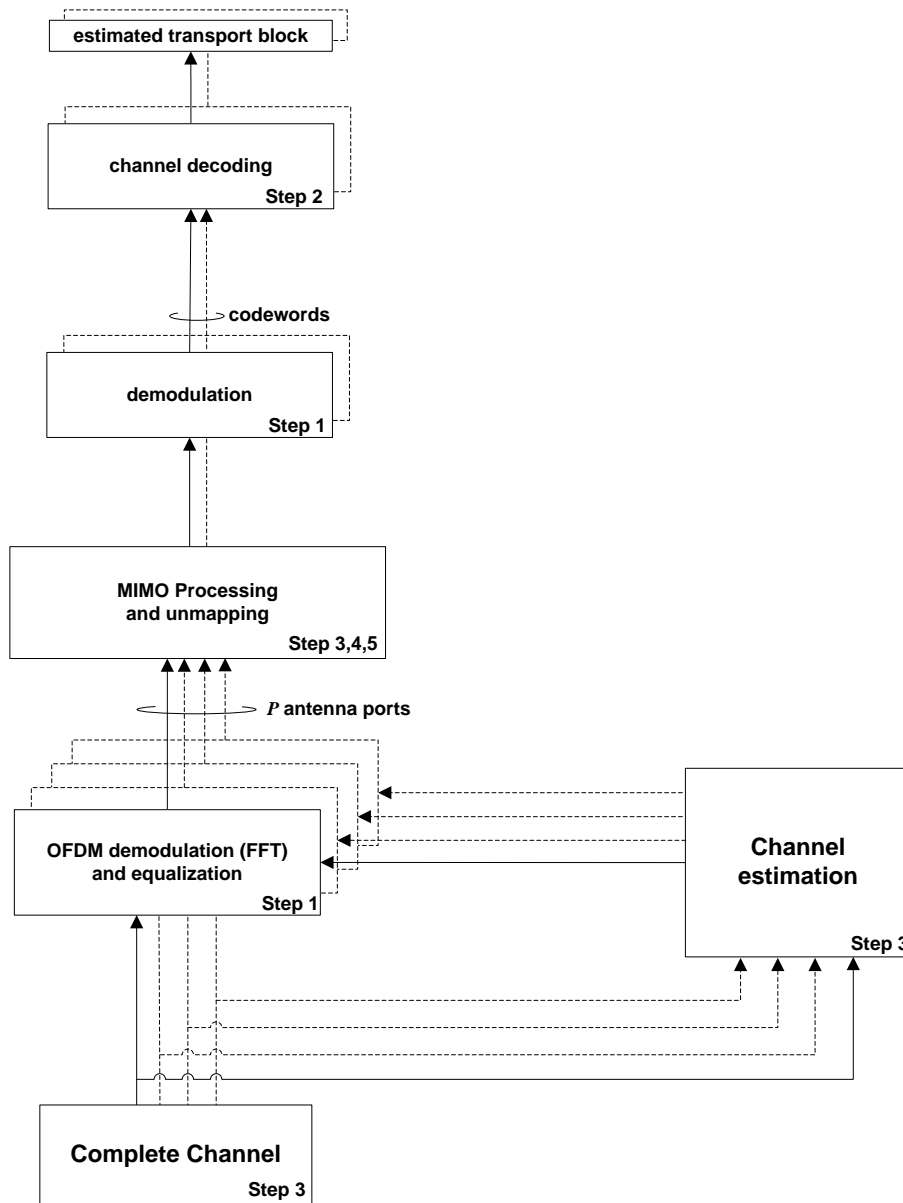

Figure 2. Simplified breaking down of the simulation chain only including the receiver part

Once the basic functional blocks have been derived, both at the transmitter and at the receiver ends, it is possible to identify subsets of functionalities, which will be defined as *macro-blocks* for the rest of this paper. These *macro-blocks* can be assessed both independently and on an end-to-end basis. Basically, the first step of the calibration process is to verify the correctness of each single *macro-block* (as will be detailed in Sections 4.1 to Sections 4.6) adding additional functionalities to the complete simulation chain in each step of the calibration. Of course, downlink and uplink will be separately simulated. Note that in Fig 2 it is indicated the specific step in which each *macro-block* is included and/or modified. Besides, for each step a proper reference for calibration is proposed. Then, in a second phase of calibration, the entire simulation chain with all functionalities should be aligned to a valid reference for the considered system configuration (as will be detailed in Section 4.7). In particular, for this latter phase some references from the 3GPP LTE Release 8 specifications are proposed [28].

Next five subsections describe the set of five calibration steps defined in WINNER+ for the downlink. Section 4.6 deals with the specific calibration of the uplink and, finally, section 4.7 explains the end-to-end calibration process of LTE performance aligned with the 3GPP. Fig 3 summarises the overall calibration process.

4.1 OFDM modulation

The first step (step 1) of the calibration process consists in the validation of the OFDM Modulation/Demodulation (OMD) unit. In order to do so, it is necessary to focus only on the inputs and outputs of this macro-block (i.e. no coding/decoding functionalities will be considered in this case) and to make some assumptions on the system parameterisation.

The following assumptions are suggested for the calibration phase: the propagation channel is fixed and ideal channel estimation is assumed with a ZF receiver. Both an AWGN channel and a Rayleigh channel should be considered in the assessment of the OMD unit. The curves obtained by simulation in this first step should overlap the theoretical reference curves that can be found in literature (see, e.g., [29]). Note that even if the Rayleigh channel is simulated with multipath curves should be equal to the theoretical curves without multipath due to the ability of the OFDM modulation to face frequency selectivity.
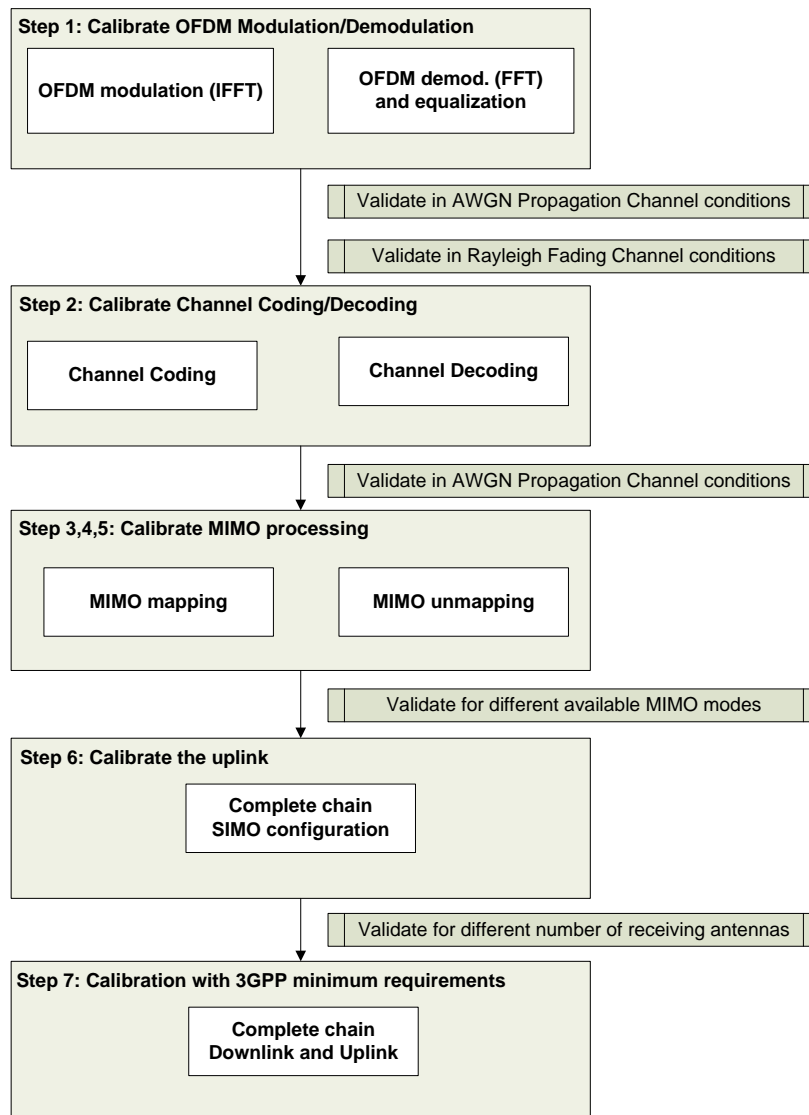
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Step 1: Calibrate OFDM Modulation/Demodulation

    OFDM modulation (IFFT)        OFDM demod. (FFT)
                                  and equalization

              ┌─ Validate in AWGN Propagation Channel conditions ─┐
              └─ Validate in Rayleigh Fading Channel conditions ──┘

Step 2: Calibrate Channel Coding/Decoding

    Channel Coding                Channel Decoding

              ┌─ Validate in AWGN Propagation Channel conditions ─┐

Step 3,4,5: Calibrate MIMO processing

    MIMO mapping                  MIMO unmapping

              ┌─ Validate for different available MIMO modes ─┐

Step 6: Calibrate the uplink

              Complete chain
              SIMO configuration

              ┌─ Validate for different number of receiving antennas ─┐

Step 7: Calibration with 3GPP minimum requirements

              Complete chain
              Downlink and Uplink
```

Figure 3. Link Level calibration process

4.2 Channel coding

In the next phase (step 2) the coding functionalities of the LTE system must be included in the link level simulator. Since the turbo coding performance depends highly on the turbo block size, from this step on the actual PDSCH frame structure must be implemented and different RB allocations have to be tested. Since the results obtained in this second step of calibration are LTE-specific, it has sense to refer directly to the internal documents of the 3GPP to perform the best-suited benchmark. For instance, in [30] turbo coding is evaluated assuming an AWGN channel, a ZF receiver and a maximum of only one HARQ transmission. This document studies the performance of the LTE system for different coding rates and number of RBs allocated to the transmission. Note that the coding chain is not exactly LTE R8 compliant and, thus, in the calculation of the block size, the

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simulations do not include the trellis termination, neither the CRC bits per segment. Besides, not any information is provided about the used internal interleaver. The results are provided in terms of relative throughput.

In addition to this, to check the exact results, some trends must be observed. First, the turbo coding relative performance is worse for small block sizes although this effect almost disappears for larger number of RBs. Nevertheless, with lower SNIR the efficiency of small block sizes is much higher than for large block sizes. This effect supports the idea of allocating small packets to users experiencing poor channel conditions.

Finally, note that, once this step is assessed, the FEC *macro-block* based on turbo coding is included in all the rest of calibration steps.

4.3 SIMO configuration

In the third step (step 3) the entire transmission chain should be simulated with the channel model described in Section 3.1. A fixed bandwidth of 10MHz – 50 RBs – is simulated assuming the realistic channel estimation explained in Section 3.3 and different channels – EPA, EVA and ETU [17] – with a SIMO 1x2 configuration [31], since this is the simpler configuration established by the 3GPP. The scenario could be validated through a direct comparison with the minimum requirements specified by the 3GPP in [28]. This validation refers to a threshold value for the system throughput for a given SNIR value. This quantity is a reference and does not represent an exact value valid for cross-checking. Besides, it is important to highlight that, with only one point, it is not possible to validate the entire system trend, most of all in the first calibration approach. For these reasons, other 3GPP internal references are recommended in this validation step. Specifically, in [32] an extensive collection of results from different manufacturers are shown and compared following the same recommendations made in this section.

4.4 MIMO configuration: Transmit diversity

Similarly, the fourth step (step 4) could validate the system by a direct comparison with the 3GPP minimum requirements [28] although it is preferred a more detailed analysis. The simulation assumptions for the assessment of the transmit diversity scheme proposed in LTE includes a MIMO 2x2 configuration with space-frequency block coding (SFBC), maximum bandwidth of 10MHz, realistic channel estimation and a ZF receiver. More details on these assumptions can be found in [33], whereas the 3GPP results used for

calibration are summarised in [34]. Since several curves are provided by the 3GPP, as an approach it is suggested to discard non-coherent results and average the remaining.

4.5 MIMO configuration: Spatial multiplexing

In the fifth calibration step (step 5) spatial multiplexing simulations are assessed. These can be divided into open loop and close loop scenarios. In case of open loop, Large-delay Cyclic Delay Diversity (CDD) precoding must be implemented following the standard. Although minimum requirements for two antenna configurations – 2x2 and 4x2 – are provided in [28], a more detailed set of results can be found in [35] and [36], respectively. On the other hand, in case of the close loop scenario, single layer and multiple layer spatial multiplexing configurations must be calibrated. Some specific results with 4x2 MIMO are summarised in [36].

4.6 Special characteristics of the reverse channel

With the previous five steps the downlink complete chain has been completely validated. The next step (step 6) consists in assessing the system in the uplink using the PUSCH (Physical Uplink Shared Channel) channel. Obviously the same five steps described for the downlink could also be valid for the reverse channel, although, given that all the *macro-blocks* have been already tested, the calibration process will continue with the complete uplink transmission chain. The simulation assumptions will include a SIMO 1x2 antenna configuration, realistic channel estimation based on MAP, MMSE receiver and complete channel modelling as described in Section 3.1. This simulation scenario corresponds to the one proposed in [37]. The minimum requirements for PUSCH are provided in the specification [38]. For the validation purpose it is suggested to refer also to the 3GPP detailed results gathered in [39].

4.7 3GPP minimum requirements of the whole transmission chain

In order to validate the link level simulators, and to ensure the comparability of the obtained results, a link level calibration methodology has been defined in the previous sections. The first phase of the calibration process has been to verify the correctness of each single functional block within the simulation chain. Afterwards, once this first phase has been fulfilled, the entire simulation chain should be aligned to a valid reference for the particular system under consideration. A possible procedure for this task can be based on the direct comparison of the End-to-End (E2E) link level simulation results with other

outcomes provided by the research community, when referring to common simulation scenarios.

In particular, comparison with the 3GPP LTE Release 8 framework can be thought as a reference for the E2E system performance, by considering the minimum values provided in [28].

To get started, the simulator parameterization should be aligned to that of Common Test Parameters proposed in [28] and [38] and refer to the demodulation of PDSCH/PUSCH for the FDD case and/or for the TDD case (depending on the duplexing mode that has been implemented in the simulator), in the following configurations:

1. Single-antenna port
2. Transmit diversity
3. Open-loop spatial multiplexing
4. Closed-loop spatial multiplexing

If possible, one should refer to each of the above configurations. For each selected configuration, one should refer to at least one significant reference channel (defined in [28] and [38]) so to vary among the different tests: propagation conditions, modulation and coding schemes (MCS) and number of used antennas. All propagation conditions (EPA, EVA, ETU, HST) are defined in [28].

Once the simulations have been performed, the obtained results (expressed in terms of 70% fraction of maximum throughput versus SNR) should be compared with the minimum performance values reported in [28] and [38], for the PDSCH and PUSCH respectively.

5. Link-to-System Modelling

As aforementioned, link level and system level simulations must be linked using a link to system (L2S) level mapping whose characteristics depend on the system under study and the needs of the system level simulation. In this section the peculiarities of OFDMA systems will be presented and the motivation to develop new L2S models explained. Then the most important OFDMA L2S models will be shown with the focus on the Mutual Information Effective SNR Mapping.

5.1 Alternatives

In the typical approach to the system modelling of UMTS, in system level simulations the wireless channel is modelled considering only the mean propagation loss and large scale

fading – also known as shadowing – while fast fading is accounted at the link level. This approach is valid in this scenario due to the way in which a UMTS transmission is spread over the whole bandwidth, which provokes a large correlation between the mean SNIR of one radio block and its correct reception. Therefore, in this scenario a simple look up table for each modulation and coding scheme is needed to translate the instantaneous SNIR to a BER or BLER value.

However, in OFDMA systems there are two important differences. First, users share subcarriers and time slots. Therefore, in order to evaluate the effect of opportunistic scheduling, in which the channel fluctuations of users are exploited to get some multi-user diversity, small-scale variations in the channel – i.e. fast fading – must be also simulated at the system level to know the specific propagation conditions of the subcarriers each user has been assigned. Besides, it has been proven that the mean SNIR experienced by the blocks allocated to a specific user is not a good channel quality measure to be translated to decoding quality (BLER). Instead, it has been demonstrated that behaviour of Forward Error Correction (FEC) techniques depends highly on how different instantaneous channel quality levels affect different coded bits. Therefore, it becomes crucial to model the behaviour of the channel in the frequency domain over both short and long time scales and new L2S models must be used in order to compress the information from a set of instantaneous channel states – that can be obtained at bit, symbol or Resource Block level – to one or two specific measures used for mapping link level data.

Although different proposals can be found in the literature (see, e.g., [13]), most common approaches are based on the Effective SNIR Mapping (ESM) concept. ESM maps an instantaneous set of SNIR samples into a scalar value. This scalar value is called effective SNIR and is calculated as

$$\phi_{eff} = \alpha_1 \Phi^{-1}\left(\frac{1}{N}\sum_{i=1}^{N}\Phi\left(\frac{\phi_i}{\alpha_2}\right)\right),$$

being N the number of SNIR samples, $\Phi \cdot$ an information measure function and $\Phi^{-1} \cdot$ its inverse, α_1 and α_2 must be calculated to fit the model to each specific MCS. Once the effective SNIR value has been calculated, a look up table obtained through simulations conducted in an AWGN scenario is used to translate the effective SNIR value to, for instance, a BLER value. An AWGN look up table must be obtained for each MCS.

Another aspect usually neglected but that must be considered when simulating LTE is related to the usage of turbo coding (TC) as FEC coding method. In TC the longer the

frame length, and thus the interleaver length, the better the turbo decoding performance, as a wider spreading of the coded bits is achieved [14]. For that reason, the system performance varies according to the number of resources allocated to each user. Consequently, link level simulation results must be obtained for different MCS and also for different number of allocated RBs.

5.2 Effective SNR mappings

There are a number of different proposed effective SNR mappings, as many as information measure functions have been used. Among all these options two have been widely used in LTE performance assessments: the Exponential ESM (EESM) and the Mutual Information ESM (MIESM).

EESM was discussed and adopted in 3GPP feasibility study on OFDM and its derivation is based on the Union-Chernoff bound for error probabilities [40][41][41][43]. Its information measure function is a negative exponential. It is remarkable that α_1 and α_2 are usually considered equal:

$$\phi_{eff} = -\alpha \ln\left(\frac{1}{N} \sum_{i=1}^{N} \exp\left(-\frac{\phi_i}{\alpha} \right) \right),$$

Simulation data shown in [41] has indicated good match of results, independent of channel models, i.e., the same factor α has been used for different channel models with the same MCS. Nevertheless performance for higher order modulations becomes worse.

MIESM method is based on another information measure called mutual [44]:

$$\phi_{eff} = \alpha I_M^{-1}\left(\frac{1}{N} \sum_{i=1}^{N} I_M\left(\frac{\phi_i}{\alpha} \right) \right),$$

The mutual information corresponding to a SNR value is not obtained through a form expression, a look up table obtained via numerical methods is used instead. Mutual information for a SNR value depends on the order of the modulation, the modulation constellation and the coding scheme. Then, in LTE three look up tables must be obtained, one for each allowed modulation (QPSK, 16QAM and 64QAM). A study conducted using a system similar to LTE demonstrated that MIESM method can provide in general better results than EESM method [13]. Based on the results of this study it can be obtained an important conclusion: EESM fitting factors are quite different for each transmission mode but MIESM fitting factors are close to 1. Therefore, EESM requires a calibration to operate

but MIESM can be used even with non-calibrated fitting factors, providing successful results.

5.3 ESM fitting

In the following the method proposed for the calibration of the ESM interface used in WINNER+ is described.

- Step 1: Simulation with AWGN channel. It is simulated any specific transmission mode over an AWGN channel to obtain the reference SNIR to BLER curve.

- Step 2: Simulations with multi-path channel. N simulations are run with the specific transmission mode and including the complete channel model. In each simulation the channel realization is different but constant during the whole duration of the simulation. From each simulation, a set of pairs $SNIR_{Mean}$-$BLER_{Mean}$ and a single channel frequency response is derived. Note that for each realization of the channel the specific BLER curve is different as sketched in Fig 4.
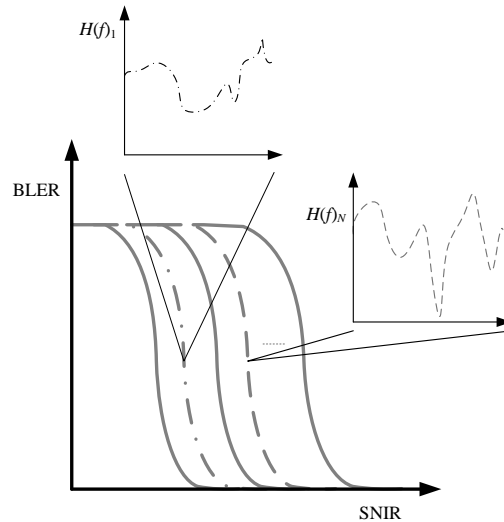

Figure 4. Link Level calibration process

Using the specific $H\left(f\right)_N$, each value of $SNIR_{Mean}$ value can be mapped to a set of SNIRs per subcarrier, ϕ_i.

- Step 3: Choice of the fitting points. After step 2, N curves $SNIR_{Mean}$-$BLER_{Mean}$ are available, each containing M points, which results in a total of N by M points. In the fitting process only a subset of $S \leq N \cdot M$ points is used. A valid option is considering only the points with BLER ranging between 10% and 80%.

- Step 3: Choice of the fitting points. After step 2, N curves SNIR$_{\text{Mean}}$-BLER$_{\text{Mean}}$ are available, each containing M points, which results in a total of N by M points. In the fitting process only a subset of $S \leq N \cdot M$ points is used. A valid option is considering only the points with BLER ranging between 10% and 80%.

- Step 4: Search of the ϕ_{AWGN} associated with each fitting point. For each one of the S points of calibration there is one BLER value. Using the curve obtained in step 1, it can be found the corresponding SNIR value that, with an AWGN channel, would provide the aforementioned BLER. From now on this value is called ϕ_{AWGN}.

- Step 5: Recursive calibration process. Starting from an initial value of α, for each fitting point the effective SNIR, ϕ_{eff}, is calculated. Finally, the calibration error is obtained as:

$$\frac{1}{S} \sum_{s=1}^{S} \left| \phi_{eff} - \phi_{AWGN} \right|^2,$$

  This process is repeated iteratively until the value of α that minimises the calibration error is found.

6. Conclusions

This paper has summarized the complete link level calibration process methodology defined in the framework of WINNER+, focussing on the key aspects of the LTE system and starting from the OFDM testing up to the link-to-system interface model verification. A detailed step-wise approach able to execute the calibration process for the link level simulator was provided. The methodology is based on breaking down the entire simulation chain into its single building blocks, identifying basic subsets of functionalities.

The first phase of the calibration process has been to verify the correctness of each single functional block within the simulation chain. Afterwards the entire simulation chain has been aligned to a valid reference for the particular system under consideration. A possible procedure for this task can be based on the direct comparison of the E2E link level simulation results with other outcomes provided by the research community, when referring to common simulation scenarios. In particular, when presenting the LTE link

level calibration methodology, we have provided a significant set of references from 3GPP documentation, strengthening and validating the overall process.

This document may represent a valuable guide for link level simulator calibration in the forthcoming EEG simulation phase, within the performance evaluation process of IMT-Advanced technology proposals, guaranteeing, when it is followed, complete consistency and comparability of the obtained results.

Acknowledgements

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