OPEN-SOURCE PHYSICAL-LAYER SIMULATOR FOR LTE SYSTEMS

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ABSTRACT

This article describes a physical-layer simulator for both uplink and downlink connections of LTE systems, whose performances are assessed by simulating standardized environments. The simulator is compliant with Release 9 of LTE standard and it is publicly available for educational purposes, allowing students and researchers to test the performance of Signal Processing and Digital Communications techniques in an easy-to-use MATLAB framework. Users may benefit from implemented features such as channel estimation using different demodulation reference signals, channel coding, equalization, multiple access schemes in which multiple cells are employed, as well as diversity, spatial multiplexing, and beamforming transmissions. As an example, we evaluate the impact on the performance of an uplink connection due to inaccuracy in channel estimation and multi-user interference. In addition, we include the evaluation of using diversity and spatial multiplexing transmissions on downlink connections.

Index Terms— Wireless communications, LTE, physical-layer simulator, multi-user interference.

1. INTRODUCTION

The progressive evolution of digital mobile communications is usually motivated by the user's demand for higher data rates. Such requirement has led to the development of new standards that incorporate the state-of-the-art signal processing techniques in order to fulfill the needs of the end users. In this context, the LTE (long-term evolution) system has brought several changes to wireless standards, especially in the radio access [1].

The LTE standard is defined by 3GPP (3rd Generation Partnership Project). 3GPP Releases are continuously provided such as the most recent version called Release 11 [2]. Some companies have already launched commercial LTE networks, e.g., Verizon Wireless in the United States and Vodafone in Europe.

This article aims to describe the LTE system simulator LTE-LPS (long term-evolution physical-layer performance simulator), which is an open-source simulator for educational purposes, developed for MATLAB, and available at [3]. Differently from [4], the LTE-LPS implements both downlink and uplink connections, according to Release 9. Emphasis is given on the uplink connection since the multi-user interference (MUI) is usually much more severe in this connection. This simulator can evaluate the bit error-rate (BER) performance as a function of the bit-energy-to-noise power ratio (E_b/N_0). In addition, it is possible to check how close the estimated magnitude response of the channel is, as compared to the actual magnitude response. In opposition to [5], our simulator is open source and simulates both uplink as well as downlink. Although [6] provides multiple network-layer simulations, LTE-LPS allows the simulation of a more complete physical-layer scenario.

This simulator may be used as a tool for studying signal processing and digital communications techniques such as channel estimation, channel coding, equalization, multiple access schemes, multiple-input multiple-output (MIMO) transmissions (diversity, spatial multiplexing, and beamforming), and MUI effects. To illustrate some of these points we study spatial multiplexing and diversity transmissions for the downlink connection, whereas for the uplink our focus is on the MUI effects and channel estimation. Besides, channel-estimation simulation results using Zadoff-Chu (ZC) sequences as demodulation reference signals are presented in an uplink-LTE scenario. Such ZC sequences were proposed in Release 8 of LTE standards [2].

This paper is organized as follows. Related works are mentioned in Section 2. The LTE-LPS simulator is described in Section 3. Some simulation results using LTE-LPS are shown in Section 4. The concluding remarks are drawn in Section 5.

2. RELATED WORKS

Other LTE-based simulators have already been published as, e.g., [4]–[7]. Table 1 presents a brief comparison among them and LTE-LPS. Each feature pointed out in this table is explained in the following. The term *yes*/*no* denotes that the related simulator *has*/*does not have* the specific feature, whereas 'N/A' is used when the information about the specific feature is not available.

Table 1. Features of LTE-based simulators.

Features\Simulator	[4]	[5]	[6]	[7]	LTE-LPS
System-level	no	no	yes	yes	no
Link-level	yes	yes	no	no	no
Downlink-data	yes	yes	no	no	yes
Uplink-data	no	no	no	no	yes
Release	8	N/A	8 & 9	8	9
Multiple cells	N/A	no	yes	no	yes
Open source and free	yes	no	yes	yes	yes
MATLAB	yes	no	no	yes	yes

The first four features are associated with the target of the simulator. A *system-level* simulator is intended to assess network-layer issues, whereas a *link-level* one aims at evaluating physical-layer

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aspects. Both classes of simulators implement transmission of user data and control information. The other two terms, namely *downlink-data* and *uplink-data* simulators, are used to denote simulators that implement only user data transmission over the physical shared channels, i.e., no control information is sent.

In addition, *release* represents the LTE version on which the simulator was based. Feature *multiple cells* denotes the possibility of considering more than one cell, which is useful to study intercede interference effects. *Open source and free* is used for simulators whose code is available for downloading and usage without any charge. The last feature, *MATLAB*, concerns the platform in which the simulator was developed. Simulators based on MATLAB are usually easier to configure and add new functionalities, but they are also more time-consuming than the ones implemented in non-interpretable languages such as C/C++.

3. THE SIMULATOR: LTE-LPS

The LTE-LPS is a physical-layer simulator based on Release 9 of LTE system. It simulates data transmission over the physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH). All functionalities of PDSCH and PUSCH regarding data transmission [8] are incorporated in LTE-LPS. In addition, it is possible to perform turbo coding [9] to protect the user data.

The main differences between downlink and uplink connections concern the *multiple access* (MA) method and the *number of antennas* used in the transmission. In the downlink, the employed MA technique is known as OFDMA (orthogonal frequency division multiple access), whereas the SCFDMA (single-carrier frequency division multiple access) is used in the uplink due to its lower PAPR (peak-to-average power ratio) [10]. Regarding the number of antennas, multiple antennas are allowed at both the transmitter and receiver sides (MIMO transmission) in downlink.[1]

3.1. Starting LTE-LPS

LTE-LPS has a flexible design, where many of its parameters can be easily changed, sometimes using configurations not defined in [8] and [9]. It is simple to use the simulator, since all parameters can be set in the *Settings.m* file, and for starting the simulation one must simply run the file *LTE_LPS.m* on MATLAB and follow the instructions on the screen. Alternatively, the *Main.m* files may be run from either Uplink or Downlink folders. A how-to-use document (see [3]) is also provided, enabling users to quickly start using the simulator.

3.2. Building Blocks

Figs. 1 and 2 depict the building-block representations related to the generation of OFDMA and SCFDMA symbols, respectively. These figures represent just the transmitter side. To each of these blocks there are corresponding blocks at the receiver which are only responsible for reverting the processing done at the transmitter. These blocks are omitted in this paper. In the following we assume that the building blocks are familiar to readers in such way we can concentrate on the different possibilities of setting them.

1. *Scrambling:* scrambles bits within a codeword.
2. *Digital modulation mapping:* bits are transformed into digital modulated symbols. The modulation is chosen among QPSK (quadrature phase-shift keying), 16-QAM (quadrature amplitude modulation), and 64-QAM constellations.
3. *Layer mapping* and *precoding:* related to the downlink MIMO transmission model. There are three possibilities [8]: transmission with a single port, with multiple ports using frequency diversity (SFBC – space-frequency block coding), or with multiple ports using spatial multiplexing [8].
4. *Resource element mapping:* maps symbols to the time-frequency grid.
5. *CP insertion:* inserts cyclic-prefix (CP). The CP size can be normal or extended [8].
6. *Channel:* introduces distortions to the transmitted signal according to a chosen channel model. There are many channel models, including the pedestrian, vehicular, and typical urban LTE channel models described in [11]. In addition, the channel accounts for carrier-frequency offset (CFO) due to user mobility and, at the end, it also adds noise to the transmitted signal. The *bandwidth* of the channel may vary from 1.4 to 20 MHz according to [11].
7. *Channel estimation:* receiver uses transmitted demodulation reference signal (DRS) to estimate the channel and subsequently use it in the channel equalizer. The channel estimation is performed in the frequency-domain using a least-squares method. Different DRSs can be chosen, including Zadoff-Chu-based (ZC) sequences [8], which are very effective in the presence of multi-user interference. DRSs are transmitted on a single OFDMA/SCFDMA symbol of every slot.
8. *Channel equalization:* receiver mitigates the effects of the channel in order to estimate the transmitted data. The channel equalization can follow a zero-forcing (ZF) or a minimum mean-squared error (MMSE) algorithm.
9. *Channel coding:* although not represented in Figs. 1 and 2, a turbo encoder is used at the transmitter to protect the user data, forming the codewords, and a turbo decoder is used at the receiver to correct errors and to recover an estimate of the data. The turbo encoder rate is 1/3 and it is very easy to modify its characteristics, e.g., the polynomials of the recursive convolutional codes within the turbo encoder, the number of subframes encoded as a single block, and puncturing allowing rates of 1/2 and 2/3. The number of iterations at the turbo decoder can also be adjusted.

3.3. LTE-LPS Features

The file *Settings.m* is configured with default parameters of LTE system. However, it is very simple to modify these parameters, i.e., the simulator is not limited to the LTE system. In addition, due to its modularity, it is also easy to add new functionalities. Therefore, we believe that LTE-LPS simulator is a valuable tool for physical-layer researchers. Moreover, we also believe that such a tool can be used for educational purposes since it can be employed to illustrate many key points present in courses like digital communications, digital transmission, and linear estimation, just to mention a few. In Section 4 we illustrate this fact by showing some results and plots that can be extracted from the simulator.

The simulator can be used to evaluate physical-layer components like channel coding, channel equalization, and strategies for resource element mapping. For downlink connections it is also possible to evaluate antenna mapping and MIMO transmission gains. For uplink connections, emphasis is given to the evaluation of (intra-cell or inter-cell) multi-user interference and channel estimation schemes employing different DRSs.

[1] Uplink MIMO transmission was only introduced in Release 10.

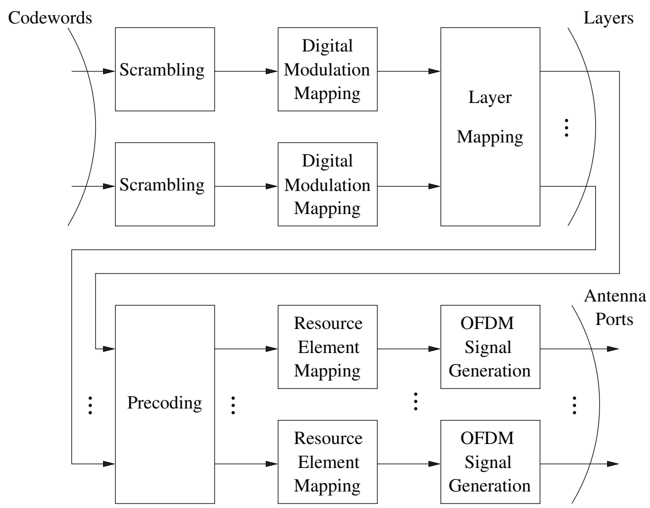

Fig. 1. Transmission scheme for the downlink connection.

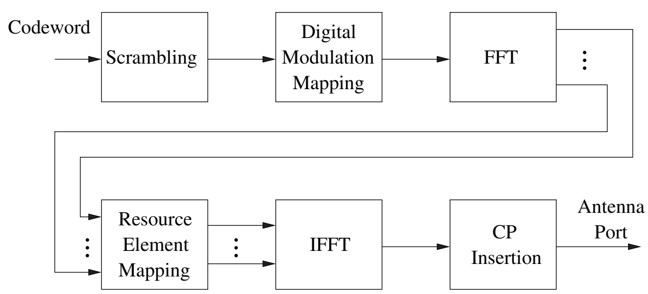

Fig. 2. Transmission scheme for the uplink connection.

4. SIMULATIONS

In this section, simulation results are shown in order to illustrate possible outcomes of LTE-LPS. The simulator parameters were chosen according to [8], [9], and [11]. The following parameters have been similarly adjusted to both downlink and uplink: coding rate is $1/3$ whenever Turbo Code is used; the CP type is extended; the channel model follows the EPA-LTE (a pedestrian channel model for the LTE system [11]); the number of iterations at the turbo decoder is 8; the user's velocity is 30 km/h; the channel bandwidth is 5 MHz and only 0.9 MHz is scheduled for the user's transmission, which corresponds to $M_{sc} = 60$ subcarriers.

4.1. Downlink Simulation Examples

This subsection illustrates advantages introduced in the LTE system by the use of multiple antennas. Fig. 3 shows simulation results for the downlink, considering that Turbo Code is on. The digital modulation used was 16-QAM.

Fig. 3(a) illustrates the gains of transmitting with diversity. One can observe that, as the number of transmit antennas grows, the E_b/N_0 required to achieve a given BER decreases, whereas Fig. 3(b) depicts the results using spatial multiplexing.

4.2. Uplink Simulation Examples

In this subsection we use the simulator to illustrate the effects of two different types of MUI: either generated by users within the same cell (*intra-cell interference* or intra-MUI) or generated by users belonging to different cells but transmitting on the same frequencies (*inter-cell interference* or inter-MUI) of the reference user. Whenever required, each of the four interferers within the same cell have the same power P as the reference user, whereas in the inter-MUI scenario the sum of the interferers' power is $P_i = 0.02P$ ($P_i \ll P$).

In Fig. 4(a), BER performance is compared for different MUI scenarios. Note that the curves corresponding to both no-MUI (only the reference user in the system) and intra-MUI scenarios present very close performance. One can observe that inter-MUI scenario causes a stronger degradation in terms of BER performance, as expected. Moreover, the BER performance using ZC-based DRS for inter-MUI is almost the same as in the case where the receiver knows the channel state information (CSI). Indeed, the benefits of ZC-based DRSs for channel estimation can be observed in Fig. 4(b).

Another possible outcome of LTE-LPS is depicted in Fig. 5. In this figure it is possible to visualize channel equalization effects for symbols belonging to a 16-QAM constellation at $E_b/N_0 = 30$ dB.

5. CONCLUSIONS

In this paper, a physical-layer simulator for the LTE system, named LTE-LPS, was introduced. LTE-LPS is a valuable educational tool which provides some key elements to those interested in understanding and evaluating various physical-layer aspects related to Signal Processing and Digital Communications techniques employed in both downlink and uplink LTE connections. Such techniques include, but are not limited to: channel estimation, channel coding, multiple access schemes, MIMO transmissions (diversity, spatial multiplexing, and beamformer), and MUI effects. The simulator, available at [3], is compliant with Release 9 of LTE standard. Possible outcomes generated by LTE-LPS are included in the paper.

LTE-LPS has been used as an auxiliary tool for teaching at an undergraduate level. For example, after explaining the theory of digital modulation, experiments like the one depicted in Fig. 5 have been used to motivate the study of channel coding and equalization techniques.

Among the next steps, we intend to improve LTE-LPS by performing bit-loading schemes, which require the implementation of a feedback channel.

6. REFERENCES

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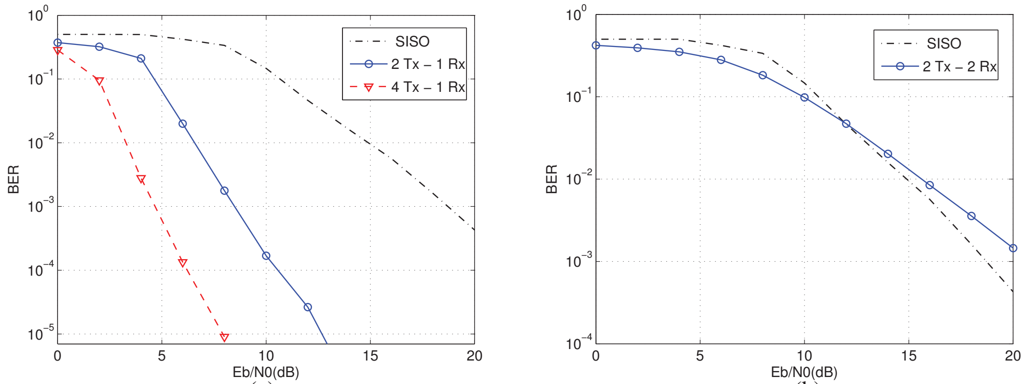
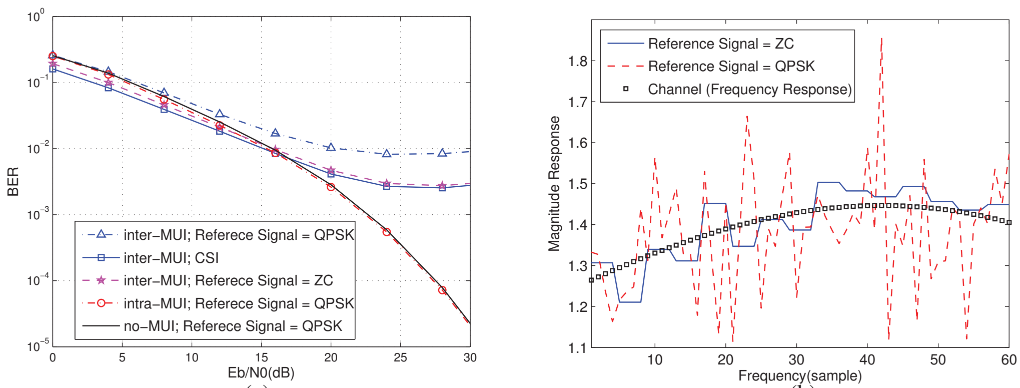


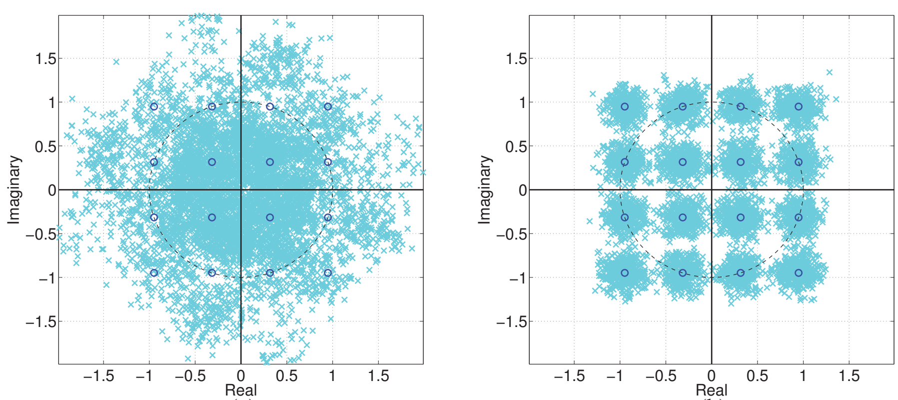
(a) (b)

Fig. 3. Downlink transmission (Turbo Code on): (a) diversity transmission and (b) spatial multiplexing.



(a) (b)

Fig. 4. Uplink transmission (Turbo Code off): (a) intra-MUI vs. inter-MUI and (b) channel estimation.



(a) (b)

Fig. 5. Received symbols in uplink transmission with $E_b/N_0 = 30$ dB: (a) before equalization and (b) after equalization.

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