Simulating the Long Term Evolution Uplink Physical Layer

Jiri Blumenstein*†, Josep Colom Ikuno*, Jan Prokopec†, Markus Rupp*
*Institute of Telecommunications, Vienna University of Technology
Gusshausstrasse 25/389, A-1040 Vienna, Austria
†Department of Radio Electronics Brno University of Technology
Purkynova 118, 612 00, Brno, Czech Republic
Email: xblume00@phd.feec.vutbr.cz, jcolom@nt.tuwien.ac.at, prokopec@feec.vutbr.cz, markus.rupp@tuwien.ac.at
Web: http://www.nt.tuwien.ac.at/ltesimulator

***Abstract*—This paper describes an open LTE uplink link level simulator. The simulator is developed using MATLAB and is offered under an academic non-profit license, including source code. This release model allows for results to be easily and openly reproduced, which tackles the common problem found in signal processing research in which reproducing the work of others is either highly complex or just not possible. This paper presents the basic structure of the simulator, as well as first results for AWGN channels showing BER and throughput performance.**

***Index Terms*—LTE, uplink, Link level simulation.**

I. Introduction

Link level simulations are needed in order to evaluate physical layer procedures. In the case of Long Term Evolution (LTE), the new iteration in wireless standards from the 3rd Generation Partnership Project (3GPP), the physical layer is based on Orthogonal Frequency Division Multiple Access (OFDMA), as opposed to UMTS, which was based on Wideband-CDMA (WCDMA). The new physical layer offers many advantages, such as high flexibility in bandwidth allocation and not needing complex time-domain equalization such as the one present in WCDMA system. However, it presents new challenges, such as in channel estimation [2], frequency offset correction [3], HARQ modeling [4], or feedback calculation [5].

In this paper, an LTE uplink link level simulator is presented. While an open LTE downlink link level simulator already exists [6], to the author's knowledge, no solution for the uplink exists. While using a similar structure, the LTE uplink employs Single-carrier FDMA (SC-FDMA), as opposed to the OFDMA-based downlink, thus performing differently. Building on top of the base from [6], given the structural similarities between uplink and downlink, which share common blocks such as channel coding, we implemented an uplink counterpart to the simulator presented in [6] based on the 3GPP Release'8 LTE standard [7–9].

When developing new algorithms in signal processing, comparison with prior and other state-of-the-art methods is of paramount importance. However, given the complexity of modern communication systems, comparisons are usually either excruciatingly complex due to lack of a complete description (often due to lack of space), lack of data, tools, or a combination of the latter [10]. Addressing the above, the LTE uplink simulator presented in this paper is released under a free non-commercial, academic use license. Such a release model enables algorithms to be tested and compared using a common, known, and verifiable environment. We are certain this openness not only improves the quality of the published results but also its credibility.

The remainder of this paper is organized as follows: In Section II, the LTE uplink chain is described, subsequently describing the simulator implementation in Section III. Section IV presents Bit Error Ratio (BER) and throughput performance results based on Additive White Gaussian Noise (AWGN) simulations. We conclude the paper in Section V, with Section VI providing a short outlook on the future of the simulator.

II. LTE uplink

In this chapter, we give an insight on the transmitter and the receiver structure of the LTE uplink, as well as the 3GPP LTE standard on which they are based.

A. Transmitter

The description of the signal processing of a Transport Block (TB) is given in the following subsection.

The TB is passed from the Uplink Shared Channel (UL-SCH) transport channel. The physical layer procedures include, as described in [8], a 24-bit TB Cyclic Redundancy Check (CRC), followed by a segmentation in Code Blocks (CBs) due to the finite size of the turbo coder interleaver and CB CRC addition. The output of the segmentation is coded by the 1/3 turbo code subsequently rate-adjusted in the rate matcher. The CBs are finally concatenated and the coded TB is then output. The whole process is depicted in Figure 1.

In the next part of this section, we describe our transmitter model, as specified in the 3GPP LTE standard. Firstly, the specific uplink modulation will be presented, then the subcarrier mapping, the LTE time-frequency grid and at the end a short view on the Channel Quality Indicator (CQI).

1) SC-FDMA modulation: SC-FDMA gets a priority for the LTE uplink before the well known and proved OFDMA due to the effort of minimizing the Peak to Power Ration (PAPR)

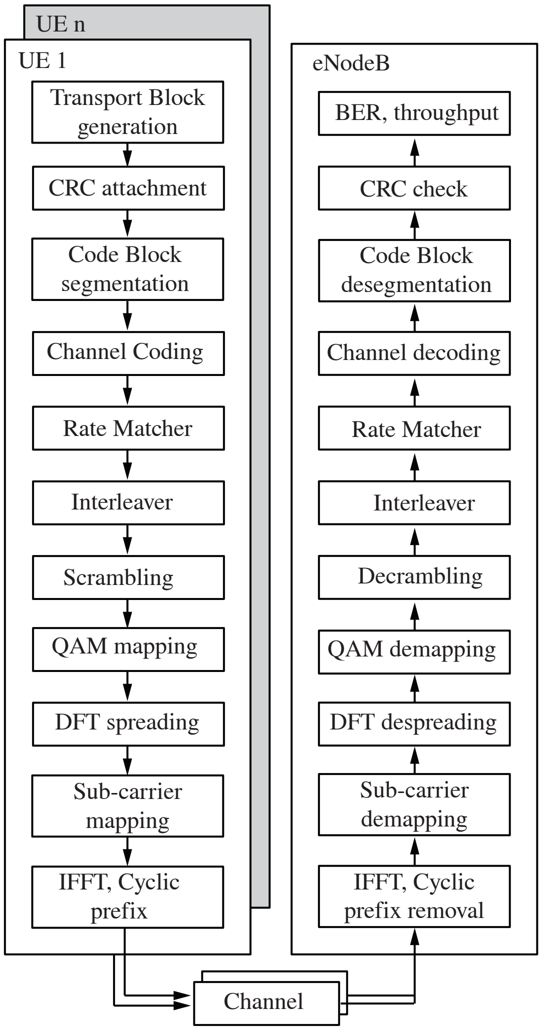

Fig. 1. Signal Processing chain used in the LTE uplink link level simulator. Shown blocks are according with [7–9]

in the uplink part of the LTE physical layer. The PAPR was determined critical because of the battery constrain on User Equipment (UE) side as well as a demanding construction of sufficiently linear power amplifiers. [11]

SC-FDMA modulation is based on the Orthogonal Frequency Division Multiplexing (OFDM) approach. However, a Discrete Fourier Transform (DFT) precoding of the signal is employed. This operation spreads individual subcarriers which are known from the OFDM system over the assigned bandwidth and convert it to a single-carrier transmission, thus effectively reducing the PAPR.

2) Subcarrier mapping: A need exists for adding zero subcarriers into the frequency grid in order to acheive appropriate size of the Fast Fourier Transform (FFT) and Inverse FFT (IFFT) operations in the receiver and the transmitter parts respectively. This add operation is driven by a subcarrier-mapping algorithm. In our simulator, the localized mapping is employed. However, besides the localized mapping, there also exists the distributed subcarrier mapping.

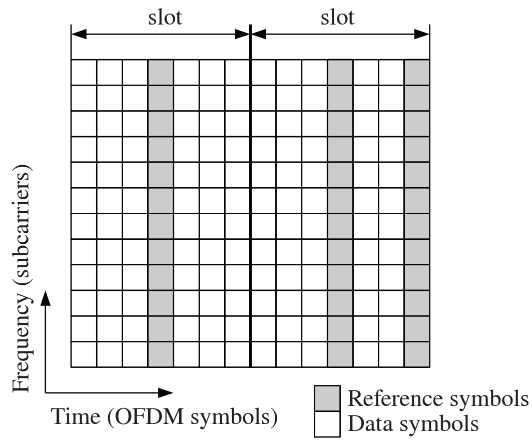

Fig. 2. Uplink Time-Frequency grid with reference symbols used in the LTE uplink link level simulator

The distributed mapping has been examined in literature [12, 13], and simulations showed only a small improvement in terms of BER performance over the localized mapping. However, it is expected that in a real system the performance will be better for the localized mapping due to simpler scanning of the channel transfer function. Moreover, the distributed mapping brings additional complexity to the system, thus the localized mapping is the choice for LTE uplink.

3) The LTE time-frequency grid: The time-frequency grid of the LTE uplink consists of so-called Resource Elements (REs). In the time and frequency domain, the grid is divided into 1 ms-long subframes and 180 kHz Resource Blocks (RBs) respectively (see Figure 2). The REs are in fact the elementary time-frequency spaces used for transmission of one data symbol from the used constellation diagram (4-, 16-, or 64-QAM). When using 15 kHz subcarrier spacing and normal Cyclic Prefix (CP) length [7], a RB consists or twelve subcarriers and one subframe of 14 OFDM symbols. For transmission of the reference signals, three OFDM symbols are needed in a subframe. This reference signals are exploited for channel estimation and demodulation purposes.

4) Channel Quality Indicator: Channel state information is reported by the UE by means of CQI reporting. The four-bit CQI value reports the highest possible Modulation and Coding Scheme (MCS) from a predefined set that is supported with the current sensed channel conditions while ensuring a Block Error Ratio (BLER) lower or equal to 10%, as in the downlink [9]. The modulation and coding scheme information for uplink is transmitted via the physical control channel in the downlink. Due to this fact, CQI values are utilized for the selection of the modulation order and coding scheme. By the standard definition, the CQI value is calculated on UE side and reported back to the eNodeB.

The CQI value contains in fact two pieces of information: Modulation Order (4-QAM, 16-QAM, or 64-QAM), and the Effective Code Rate (ECR). After the 1/3 turbo coder employed in the LTE uplink, the rate matcher module adjusts the output ECR to the desired value. The ECR thus describes the level of redundancy after the rate matching operation, as expressed in [14].

The ECR, which is in [7] described as $\mathrm{ECR} = 1024\frac{c_R}{e_R}$, where c_R is the number of useful data plus CRC and e_R is the number of output coded bits. The target ECR value is then used for TB size determination. The allowed TB sizes are given in [8], and take into account the modulation order and number of RBs assigned by the system to the UE. Combined with the resource grid size, the maximum number of bits transmitted over the physical layer can be determined.

B. Receiver

Signal processing at the receiver is inverse to the transmitter. Firstly, the CP is removed, then the IFFT is calculated and the reference signals are removed. The data is split according to the number of UEs and the assigned number of RBs. At this point, the DFT precoding is removed. Afterwards, the receiver algorithms is called, which currently is implemented via hard demapping. Figure 1 depicts the receiver chain, including the complete channel decoding, code block concatenation, and CRC calculation. After decoding the data, BER, BLER and throughput are evaluated.

III. LTE UPLINK LINK LEVEL SIMULATOR STRUCTURE

This section gives a brief introduction of the LTE uplink link level simulator implementation and its structure. First of all, it needs to be stated that the downlink part of the LTE link level simulator has been introduced in [6], and the uplink implementation follows the same basic simulator structure and implementation concept as in the downlink. The simulator implementation structure is shown in Figure 3.

The simulation is performed in the main loop as shown in Figure 1: for given a CQI value/s and corresponding Signal to Noise Ratio (SNR) vector, appropriate simulation parameters are loaded, which run the simulation for a configurable number of subframes (typically in the order of thousands to ensure appropriate BLER accuracy). The control channels are not implemented, their positions being filled with random data.

The simulator currently implements an AWGN uplink channel, while the ACK/NACKs, which are calculated after decoding and transmitted back to the eNodeB, use an error-free genie feedback channel. Perfect channel knowledge is exploited so far; the reference symbols are filled with zeros. After processing all subframes of a given vector SNRs, the CQI value is shifted and the entire process with given SNRs runs again.

The simulator parameters can be configured in the `LTE_UL_sim_batch.m`, which batch-calls the simulator and contains the CQI loop, and `LTE_UL_load_parameters.m`, which specifies simulator configuration parameters. There, the number of simulated subframes and SNR values can be configured, as well as parameters like the number of UEs and bandwidth. BER and throughput plots are shown after the simulation as figures of merit, enriched by confidence intervals.

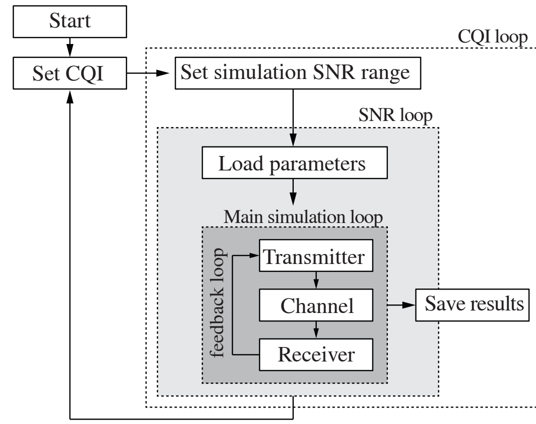

Fig. 3. Structure of the LTE uplink link level simulator

TABLE I
LTE SYSTEM PARAMETERS OF THE PRESENTED SIMULATIONS

System Bandwidth	1.4 MHz
Subcarrier spacing	15 kHz
Subframe duration	1 ms
Number of UEs	1
Number of eNodeBs	1
Antenna Scheme	SISO
CP length	'normal' [7]
Channel	AWGN
Modulation	4-QAM, ECR $\in \{78, 120, 193, 308, 449, 602\}$
and	16QAM, ECR $\in \{378, 490, 616\}$
Coding Schemes	64QAM, ECR $\in \{446, 567, 666, 772, 873, 938\}$

IV. RESULTS

Current results of the proposed simulator are shown on Figures 4 and 5. The 99 % confidence intervals are plotted in order to provide a statistical perspective on the accuracy of the presented data.

Figures 4 and 5 show BER and throughput performance results of LTE uplink simulations for the 15 MCSs specified in Table I. Compared to downlink results presented in [6], and after applying a correction factor for the fact that in uplink, three symbols are reserved for pilots, while downlink only uses two.

Compared to throughput results, Figure 5 depicts the achievable system capacity as a theoretical upper bound. The achievable system capacity is given by Shannon's formula [15], adjusted to the particular system overheads in LTE uplink:

$$C = FB\log_2(1 + \mathrm{SNR}), \qquad (1)$$

where B denotes the bandwidth of the simulated system, as in (3), SNR denotes the Signal to Noise Ratio, and F is a correction factor reflecting a reference losses due to Cyclic Prefix:

$$F = \frac{11}{14}\frac{T_{\mathrm{frame}} - T_{CP}}{T_{\mathrm{frame}}}. \qquad (2)$$

The fraction $\frac{11}{14}$ gives the reference symbol losses. Out of the

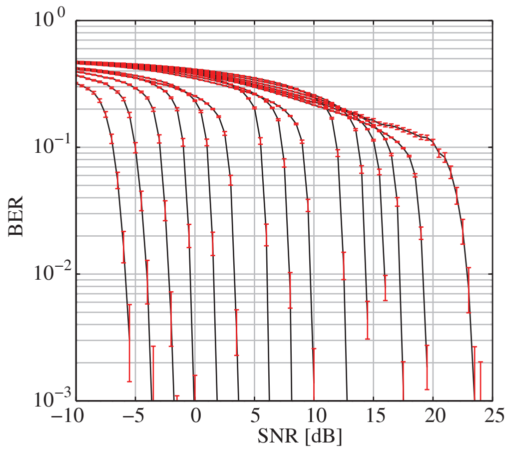

Fig. 4. Bit Error Ratio for different CQIs. Simulation parameters are shown in Table I. The 99 % confidence intervals are depicted red.

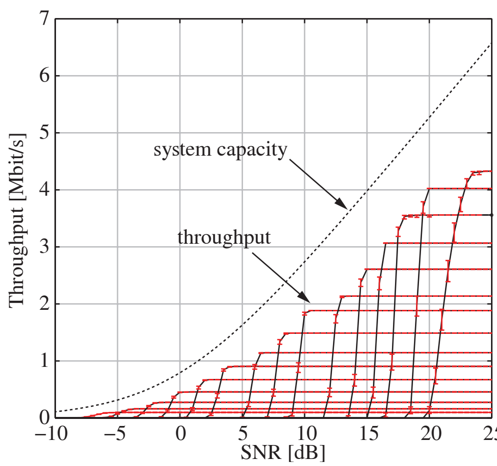

Fig. 5. Throughput curves for different CQIs with depicted confidence intervals and compared to system capacity (dotted line)

total of 14 OFDM symbols in the subframe, 11 are used for data, while 3 carry the Demodulation Reference Signals and Sounding Reference Signals.

The used system bandwidth B can thus be expressed as

$$B = \frac{N_{\mathrm{sc}} N_{\mathrm{s}} N_{\mathrm{rb}}}{T_{\mathrm{sub}}}, \quad (3)$$

where N_{sc} is the number of subcarriers in one RB, N_{s} is the number of OFDM symbols in one subframe, and N_{rb} is the number of RBs.

V. Conclusion

We presented an open LTE uplink link level simulator, implemented in MATLAB and available under a free academic non-commercial use license. The uplink simulator is based on the structure of the open downlink simulator presented in [6]. The shown AWGN performance results confirm the ability of the simulator to work according to the 36' series 3GPP standards and enables easy reproducible research in the field of LTE uplink.

VI. Outlook and Future Work

Further development and extension of the LTE uplink link level simulator include the distributed subcarrier mapping, due to the effort to push the current state of the art towards LTE Advanced (LTE-A). Works on Hybrid Automatic Repeat Request (HARQ) need to be completed and other receivers, such as Soft Sphere Decoding (SSD), are to be integrated. Last but not least, Multiple-Input Multiple-Output (MIMO) simulations and channel estimation will be implemented as well.

Acknowledgment

This work has been funded by the European Community's Seventh Framework Programme (FP7/2007-2013) under grant no. 230126 and is also supported by the research program of Brno University of Technology, "Electronic Communication Systems and New Generation Technology (ELCOM)" MSM0021630513, as well as the Institute of Telecommunications from the the Technical University of Vienna. The authors would also like to thank Michal Šimko for many fruitful and interesting discussions on this and related topics.

References

[1] [Online]. Available: http://www.nt.tuwien.ac.at/ltesimulator/

[2] M. Šimko, C. Mehlführer, T. Zemen, and M. Rupp, "Inter-Carrier Interference Estimation in MIMO OFDM Systems with Arbitrary Pilot Structure," in *Proc. IEEE VTC Spring 2011*, Hungary, May 2011.

[3] Q. Wang, C. Mehlführer, and M. Rupp, "Carrier frequency synchronization in the downlink of 3GPP LTE," in *Proceeding of the 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'10)*, Istanbul, Turkey, Sep. 2010.

[4] J. C. Ikuno, C. Mehlfürer, and M.Rupp, "A novel LEP model for OFDM systems with HARQ," in *Proc. IEEE International Conference on Communications (ICC) 2011*, June 2011.

[5] S. Schwarz, M. Wrulich, and M. Rupp, "Mutual information based calculation of the precoding matrix indicator for 3GPP UMTS/LTE," in *ITG International Workshop on Smart Antennas (WSA)*, Bremen, Germany, February 2010.

[6] C. Mehlführer, M. Wrulich, J. C. Ikuno, D. Bosanska, and M. Rupp, "Simulating the Long Term Evolution physical layer," in *European Signal Processing Conference (EUSIPCO)*, Glasgow, Scotland, August 2009.

[7] Technical Specification Group RAN, "E-UTRA; physical channels and modulation," 3GPP, Tech. Rep. TS 36.211 Version 8.7.0, May 2009.

[8] ——, "E-UTRA; multiplexing and channel coding," 3GPP, Tech. Rep. TS 36.212, March 2009.

[9] ——, "E-UTRA; physical layer procedures," 3GPP, Tech. Rep. TS 36.213, March 2009.

[10] P. Vandewalle, J. Kovačević, and M. Vetterli, "Reproducible research in signal processing," *IEEE Signal Process. Mag.*, vol. 26, no. 3, pp. 37–47, May 2009. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4815541

[11] R. Marsalek, "On the reduced complexity interleaving method for ofdm papr reduction," *Radioengineering*, vol. 15, no. 3, Sep. 2006. [Online]. Available: http://www.radioeng.cz/fulltexts/2006/06_03_49_53.pdf

[12] B. E. Priyanto, H. Codina, S. Rene, T. B. Sorensen, and P. Mogensen, "Initial Performance Evaluation of DFT-Spread OFDM Based SC-FDMA for UTRA LTE Uplink," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, 2007.

[13] S. Sesia, I. Toufik, and M. Baker, *LTE, The UMTS Long Term Evolution: From Theory to Practice*. John Wiley & Sons, 2009.

[14] P. Frenger, S. Parkvall, and E. Dahlman, "Performance comparison of HARQ with chase combining and incremental redundancy for HSDPA," *Proc. VTS IEEE 54th Vehicular Technology Conference Fall VTC*, 6001.

[15] C. E. Shannon, "A mathematical theory of communication," *Bell Systems Technical Journal*, vol. 27, pp. 379–423,623–656, 1948.