Vienna LTE-A Simulators
LTE-A Uplink Link Level Simulator
Documentation, v1.6

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Abstract

This document contains documentation on how to use the Long Term Evolution Advanced (LTE-A) Uplink Link Level simulator [1] from the Vienna LTE-A simulator suite, as well as some insight on its structure and the assumptions that were made while developing it. This document gives an introduction on how to use the simulator. The concept and the structure of the simulator is described in more detail in [2] and in [3].

I. Foreword

The LTE-A Uplink Link Level simulator is published under a non-commercial academic use license. Please make sure that you understand the terms and conditions of the license before you use any of the available software packages. Would you require a license different to a non-commercial academic one please contact Stefan Schwarz, Stefan Pratschner.

The detailed license agreement for the LTE-A Uplink Link Level simulator can be found in Section XVII. Please read the license agreement carefully, as parts of the code are under the GNU Lesser General Public License [4], and the MIT License [5].

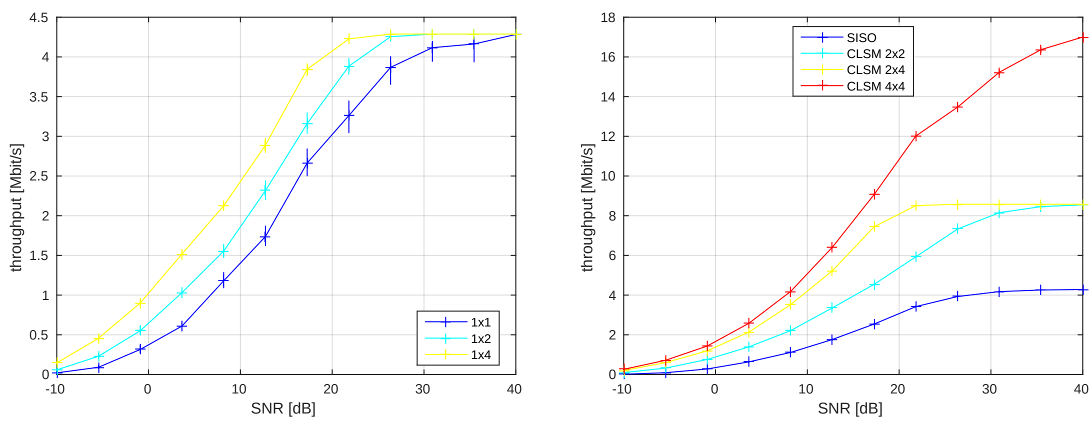
Contents

II. Running the simulator for the first time

The LTE-A Link Level Uplink simulator is provided with several test simulation scenarios that can be used to verify that the simulator runs in the expected way.

To verify that the simulator is working properly you can execute the `LTE_UL_quicktest` MATLAB script. This script contains three simulations. Two simulations should test the performance of a single user LTE-A transmission on an uncorrelated TU channel for several transmission modes [6] and antenna configurations (number of transmit antennas N_t times number of receive antennas N_r). All simulated transmission modes (Single-Input Single-Output (SISO) and Closed Loop Spatial Multiplexing (CLSM)) utilize UE feedback to adapt important transmission parameters (code rate, modulation alphabet, Multiple-Input Multiple-Output (MIMO) preprocessing) to the channel quality (see [7] for details). The third simulation shows the MUMIMO capability of the simulator.

The first simulation contains three subsimulations with a different number of receiver antennas $(1$, 2 and $4)$ and the results are shown in Figure 1a. The second simulation compares the SISO case to different MIMO scenarios and should produce the results shown in Figure 1b. Lastly the third simulation compares the performance of 4 users with 4 antennas each connected to a base station with 4 receive antennas (CLSM) applying single user MIMO and 4 users equiped with antenna one antenna each in the Multi User Multiple-Input Multiple-Output (MU-MIMO) transmission mode. The results are shown in Figure 2.



(a) receive Diversity (b) MIMO

Fig. 1: First two plots resulting from running the `LTE_UL_quicktest.m`, MATLAB script. 1.4 MHz, TU channel, zero-delay feedback, single user.

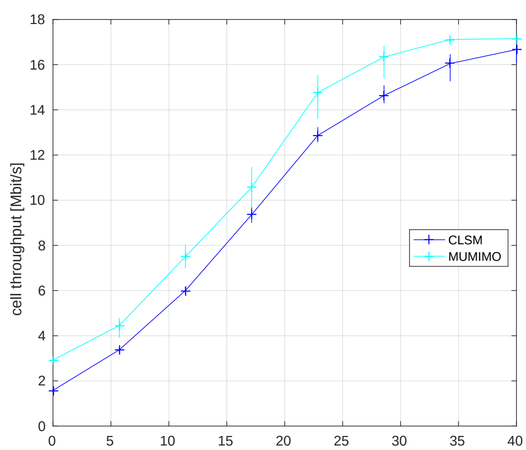


Fig. 2: Third plot produced by `LTE_UL_quicktest.m` - shows MU gain in the cell throughput. In both cases 4 users are simulated. While in the MIMO case the users are scheduled with round robin in the MU-MIMO case all users are transmitting simultaneously.

The basic parameters are defined in the configuration scripts `doc_simo.m`, `doc_mimo.m` and `doc_mumimo.m` in the `./examples/` directory. The rest of the parameters are loaded from the parameter script `./examples/load_params_doc_antenna`. For the plots We set the number of subframes to 50 (20 in the MU-MIMO case) in the release version of the quicktest file (even at this number especially the $4x4$ configuration needs quite some time). Due to the small number of subframes the results might differ a bit from the ones in the documentation which can also be seen from the plotted confidence intervals. If you want a faster simulation you can decrease the number of subframes in the configuration files by setting `simulation.N_subframes` to a smaller number. If you want slower but more accurate results you need to increase the number of subframes and probably consider running the simulation over night.

Parameter	Value
Number of UEs	1
Bandwidth	1.4 MHz
HARQ Retransmissions	0
Uplink delay	none
Channel type	TU uncorrelated
Filtering	Block Fading
Receiver type	MMSE
Simulation length	50 (2000) subframes
Transmit modes	1×1, 1×2, 1×4, CLSM 2×2, 2×4, 4×4, MUMIMO 1×4

TABLE I: Basic settings used in the `LTE_UL_quicktest.m`

III. MEX FILES

Computation-intensive parts of the LTE-A Uplink Link Level simulator are implemented in C and used in the simulator by means of MEX files. The source code for the given files can be found in the `/C-source` folder under the simulator root folder. Please note that some of the functions there are licensed under other license terms. Please check Section XVII for more details.

The MEX files distributed with the simulator release are the Windows 64-bit version. Should you require them for any other platform you recompile them by using the `LTE_aux_mex_files` script. You can find more information on how to use/write/compile MEX files at `http://www.mathworks.com/support/tech-notes/1600/1605.html`.

IV. RUNNING YOUR OWN SIMULATIONS

While the `LTE_UL_quicktest` MATLAB script is adequate to see if the simulator produces reasonable results, you might need more flexibility than given by this.

If you want to start creating your own simulations you can check the `LTE_UL_sim_batch.m` script. It provides the means to set basic simulation parameters (SNR range, number of subframes simulated, choice of simulation configuration) and calls all necessary scripts in the appropriate order.

Below you can find a list of exemplary parameters that you may want to configure in the batch file:

- `cqi_vec`: set of Modulation and Coding Schemes (MCSs) that are used for the simulation. In [8], 15 different Channel Quality Indicators (CQIs) are specified. If you want to simulate with all possible CQIs, just set the `cqi_i` loop to run over `[1:15]`. Usually you want to set this to a single CQIs to do only one simulation. This is especially useful if you use CQI-Feedback (i.e. `LTE_params.UE_config.CQI_fb = true`) to determine the CQI value automatically depending on the current channel conditions.
- `N_subframes`: the length of the simulation, or how many subframes (Transmission Time Intervals (TTIs)) are simulated for each value of `cqi_i` and `SNR_vec`.
- `SNR_vec`: a vector containing the average Signal to Noise Ratios (SNRs) that will be used for each simulation run. All users will experience the same average SNR.
- `LTE_UL_load_parameters`: load the parameter file that configures the simulator. A more detailed description of the available configuration parameters can be found in Section V.
- `LTE_UL_sim_main`: main routine of the simulator.
- Generate the output filename and save the results in a `.mat` file.

V. SIMULATION PARAMETERS

Below you can find a list of the parameters that can be configured in `LTE_UL_load_parameters`

A. General parameters

- `LTE_params.nUE`: Number of UEs per eNodeB to simulate. Each eNodeB serves `LTE_params.nUE` UEs. The total number of users is therefore `LTE_params.nBS` · `LTE_params.nUE`.
- `LTE_params.nBS`: Number of eNodeBs (cells) that will be simulated.
- `LTE_params.downlink_delay`: the delay the downlink experiences. It applies to ACKnowledgments (ACKs), CQI, Precoding Matrix Indicator (PMI) and Rank Indicator (RI) reports.
- `LTE_params.show_plots`: whether plots are shown after the simulation or not.
- `LTE_params.to_plot`: a cell array containing the plots that shall be shown after the simulation completes. If for example {`'throughput_user','bler_user'`} is given only the throughput and block error plots are shown. Passing an empty array (eg. {}) all available plots are displayed. All plots can be produced at a later point in time by using `LTE_UL_plot_results(simulation_results, LTE_params)`.
- `LTE_params.confidence_interval_probability` specifies the probability that your results lie in the displayed confidence interval. By using the default value 0.95 the confidence interval marks the interval where 95% of the results are expected (assuming the result interpreted as a random variable is Gaussian). If no confidence intervals are required set this parameter to 0. This option makes use of `bootci`, if this function is not available to you set this parameter to 0.
- `LTE_params.carrier_freq_UP`: carrier center frequency [Hz]
- `LTE_params.Bandwidth`: system bandwidth. Allowed values are 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. This bandwidths are equivalent to 6, 15, 25, 50, 75, and 100 Resource Blocks (RBs) respectively. Carrier aggregation (to enable bandwidths $>$ 20 MHz) is currently not supported by the LTE-A simulator.
- `LTE_params.HARQ_processes`: number of parallel Hybrid-ARQ (HARQ) processes. The maximum value, according to [9] is 8.
- `LTE_params.max_HARQ_retransmissions`: maximum number of HARQ retransmissions, not including the original transmission. This feature is currently not supported.
- `LTE_params.SubcarrierSpacing`: in Hz, 15 kHz only for uplink.

- LTE_params.CyclicPrefix: cyclic prefix length [10]. Either normal or extended.
- LTE_params.DFT_spreading_off: Turns off the DFT spreading in the SC-FDMA modulation when set to true. This leads to a OFDM like (downlink) performance in some sense.
- LTE_params.simulation_method: the simulator is capable of using the MATLAB Parallel Toolbox in order to speed up simulations by using parfor loops. If you happen to have the Distributed Computing Toolbox, you will also be able to make use of it by using this option. Set this variable to parallel or normal to parallelize the SNR loop in LTE_sim_main or just perform a single-core simulation. Keep in mind that some modifications you do to the code may not work in the parallel version or may directly cause it not to run.
- LTE_params.simulate_with_all_zero_sequences: true if you want that the transmitted data is an all-zero sequence (useful for interleaver testing and debugging).
- LTE_params.random_noise_seeding: whether the seed for the random number generator that generates the noise is set (allows for repeatability of the noise realizations).
- LTE_params.noise_seed: Only used if the upper variable is set to true. Integer number that sets the random number seed of the noise random number generator.
- LTE_params.connection_table specifies which user is attached to which eNodeB (BS). This parameter is a matrix with nBS rows and nUE·nBS columns of 0 and 1. A 1 in row r and column c ensures that UE number c (global numbering) is attached to BS r, while 0 stands for not connected. Not that every eNodeB needs to have the same number of UEs.
  In most cases setting the parameter by calling utils.generate_connection_table(nBS, nUE) will be sufficient.
- LTE_params.pathloss_matrix this parameter is a matrix of the same dimensions LTE_params.connection_table. The entries determine how much the signal from BS r to UE c is attenuated in dB.
  Usually it makes sense to use utils.generate_pathloss_matrix(LTE_params.connection_table, loss) to set this parameter. This attenuates the interference of other base stations by loss dB. If loss is set to inf no interference is present and the base stations do not

B. *eNodeB specific parameters*

- LTE_params.BS_config.receiver: either ZF for a Zero Forcing (ZF) receiver or MMSE for a Minimum Mean Square Error (MMSE) receiver. An additional option is the IAMMSE receiver which considers the interference of other BS in the detection process. This receiver only works with perfect channel knowledge and in UE_config.mode 1.
- LTE_params.BS_config.nRX: number of receive antennas at the eNodeB.
- LTE_params.BS_config.channel_estimation_method: Currently the following channel estimators are available for LTE-A:
  - PERFECT: Perfect channel knowledge at the receiver is used.
  - LS_AV: A least squares based channel estimation method.
  - LS_SAV: An improved least squares based channel estimation method.
  - LS_QS: A least squares based estimator applying a Quadratic Smoothing.
  - DFT: A DFT based channel estimation method from [11].
  - MMSE: A MMSE channel estimator.
  - MMSE_2D: A 2 dimensional MMSE channel estimator with MMSE interpolation in time and frequency domain. For this, the parameter LTE_params.BS_config.channel_interpolation_method also needs to be set to MMSE_2D.
- LTE_params.BS_config.channel_estimation_frequency_smoothing: In case of the LS_QS channel estimator, this parameter determines the degree of smoothing in the frequency domain. It is dependent on the number of used Layers in case of spatial multiplexing.
- LTE_params.BS_config.channel_interpolation_method: This parameter determines how the channel is interpolated between the pilot positions for estimating a FastFading (time variant) channel. Currently available options are flat (flat channel in each slot), linear, pchip (for a cubic interpolation in Matlab), spline, DPSS or MMSE_2D. Note that this parameter only affects the channel estimation for a FastFading simulation. In case of a BlockFading simulation, the two channel estimates from two slots are averaged for noise reduction as the channel is constant in time (for the whole subframe).
- LTE_params.BS_config.channel_prediction: If set to true, the wireless channel is predicted according to a method selected by the parameter LTE_params.BS_config.channel_interpolation_method. This predicted wireless channel is than exploited for calculation of feedback parameters (CQI, PMI and RI). By this, feedback delay specified by LTE_params.downlink_delay can be partly compensated.
- LTE_params.BS_config.channel_interpolation_past_points: In case of a FastFading simulation, this sets the number of channel estimates that are used for time interpolation in addition to the channel estimates of the

current subframe. Th number is given in previously transmitted slots. As the current subframe consists of two slots, a value of e.g. 1 would mean that one additional slot is used for interpolation resulting in three channel estimates that are used.

- `LTE_params.BS_config.autocorrelation_matrix_type`: type of autocorrelation matrix. Currently only `ideal` is supported.
- `LTE_params.BS_config.realization_num`: number of channel realizations. Used for averaging to obtain the channel autocorrelation matrix.
- `LTE_params.BS_config.realization_num_total`: number of channel realizations are used just for the estimation of the autocorrelation matrix.
- `LTE_params.BS_config.turbo_iterations`: Number of iterations of the turbo decoder. Set by default to 8.

C. UE specific parameters

- `LTE_params.UE_config.mode`: the transmission modes are defined in TS 36.213 V11.4 Section 8.0 [12]. However, the numbering of the implemented transmission modes is done as in the downlink. Additionally we added a transmission mode 5 which applies MUMIMO with one transmit antenna.
  - 1: single transmit antenna
  - 4: Closed Loop Spatial Multiplexing
  - 5: MUMIMO
- `LTE_params.UE_config.user_speed`: UE speed in m/s. Please note that this parameter has no effect for the setting: `LTE_params.ChanMod_config.filtering` = ’`BlockFading`’ and `LTE_params.ChanMod_config.time_correlation`=’`independent`’.

D. UE feedback specific parameters

- `LTE_params.UE_config.MCS_and_scheduling_CSI`: Weather the channel that is employed for calculating the link adaptation and scheduling is `perfect` or `estimated`. If set to `true`, still the estimated channel will be employed to calculate the linear receiver. Please note, that in case of `LTE_params.BS_config.channel_estimation_method='perfect` also perfect channel knowledge is exploited for the link adaptation and scheduling. Further, for `LTE_params.downlink_delay=0` also the perfect channel knowledge will be exploited, as the link adaptation and scheduling has to be known before transmission, which would be impossible for instantaneous downlink feedback.
- `LTE_params.UE_config.PMI_fb`: Whether PMI feedback is activated or not (`true`/`false`).
- `LTE_params.UE_config.RI_fb`: Whether RI feedback is activated or not (`true`/`false`).
- `LTE_params.UE_config.CQI_fb`: Whether CQI feedback is activated or not `true`/`false`). When set to `false` the CQI value from the batch file `LTE_UL_sim_batch.m` is used, as explained in Section IV.
- `LTE_params.UE_config.PMI`: PMI value used when `LTE_params.UE_config.PMI_fb` is set to `false`. Has to be zero if `LTE_params.UE_config.PMI_fb` is `false` and `LTE_params.UE_config.RI_fb` is `true`. Has to be a valid codebook entry if `LTE_params.UE_config.PMI_fb` and `LTE_params.UE_config.RI_fb` are `false`.
- `LTE_params.UE_config.RI`: RI value used when `LTE_params.UE_config.RI_fb` is set to `false`.
- `LTE_params.UE_config.SINR_averaging.averager`: defines the Effective Signal to Interference and Noise Ratio Mapping (ESM) averager used. Possible values are `EESM`, `MIESM`, or `HARM_MEAN`.
- `LTE_params.UE_config.SINR_averaging.EESMbetas`: defines the calibration factors required for Exponential Effective Signal to Interference and Noise Ratio Mapping (EESM). Those values are obtained from extensive training simulations and should not be changed.
- `LTE_params.UE_config.SINR_averaging.MIESMbetas`: defines the calibration factors required for Mutual Information Effective Signal to Interference and Noise Ratio Mapping (MIESM). Those values are obtained from extensive training simulations and should not be changed.
- `LTE_params.UE_config.SINR_averaging.MCSs`: defines the used MCS set. Modification of these values might lead to unexpected behavior, as the calibration factors (EESMbetas and MIESMbetas) are not trained for other MCSs.
- `LTE_params.UE_config.nTX`: number of transmit antennas at the UE.
- `LTE_params.UE_config.ignore_channel_estimation`: whether the channel estimation mean square error is taken into account during the feedback calculation or not. If channel estimation is activated, the option should be set to true, otherwise the performance of the system might be overestimated.
- `LTE_params.UE_config.channel_averaging`: whether channel averaging is used during feedback calculation or not. If set to true just a single average channel value per resource block is used to compute the feedback for complexity reduction. Especially in $\geq 4 \times 4$ systems this degrades the performance of the feedback method.
- `LTE_params.UE_config.ignore_ISI_ICI`: weather the feedback takes ISI and ICI caused by insufficient cyclic prefix length into account or not.

- LTE_params.UE_config.N_soft: Defines the total number of soft channel bits available for HARQ processing (TS 36.306 4.2.1.3 [13]).

E. Channel model parameters

Parameters that configure how the channel is generated and the signal filtered.

- LTE_params.ChanMod_config.filtering: BlockFading for a channel that is constant during one subframe or FastFading for a channel that varies in time within a subframe.
- LTE_params.ChanMod_config.time_correlation: Sets whether the channel realizations are time-correlated or not. correlated or independent.
- LTE_params.ChanMod_config.corr_coefRX: Correlation between the receiver antennas. Only compatible with block fading filtering. This parameter might be overwritten in the LTE_UL_load_parameters_generate_elements script file.
- LTE_params.ChanMod_config.corr_coefTX: Correlation between the transmitter antennas. Only compatible with block fading filtering. This parameter might be overwritten in the LTE_UL_load_parameters_generate_elements script file.
- LTE_params.ChanMod_config.interpolation_method: Channel interpolation method for the channel generation in the simulator. Either shift_to_nearest_neighbor for nearest neighbor interpolation or sinc_interpolation for sinc interpolation, which is more precise. Necessary if the channel sampling rate is not equal to the sampling rate of the transmit signal.
- LTE_params.ChanMod_config.sin_num: specifies the number of sin realizations used for the modified Rosa-Zheng model [14], [15].
- LTE_params.ChanMod_config.tau_rms: Is the RMS delay spread of the ePDP channel model.
- LTE_params.ChanMod_config.type: specifies the type of channel used. The available ones are:
  - AWGN: Additive White Gaussian Noise channel.
  - flat Rayleigh: temporally uncorrelated frequency flat Rayleigh fading channel.
  - Tap-delay based models: PedA, PedB, PedBcorr, VehA, VehB, TU, RA, ePDP, and HT [16], [17].
  - Externally-generated channel coefficients: winner_II. Uses the publicly-available Winner II implementation to generate the channel coefficients [18]. The following parameters can be configured when using the Winner II channel model.
    * LTE_params.ChanMod_config.winner_settings.Scenario: 1=A1, 2=A2, 3=B1, 4=B2, 5=B3, 6=B4, 7=B5a, 8=B5c, 9=B5f, 10=C1, 11=C2, 12=C3, 13=C4, 14=D1 and 15=D2a.
    * LTE_params.ChanMod_config.winner_settings.PropagCondition: LOS or NLOS.
    * LTE_params.ChanMod_config.winner_settings.SampleDensity: number of time samples per half wavelength
    * LTE_params.ChanMod_config.winner_settings.UniformTimeSampling: use same time sampling grid for all links (yes or no).
    * LTE_params.ChanMod_config.winner_settings.FixedPdpUsed: nonrandom path delays and powers (yes or no).
    * LTE_params.ChanMod_config.winner_settings.FixedAnglesUsed: nonrandom AoD/AoAs (yes or no).
    * LTE_params.ChanMod_config.winner_settings.PolarisedArrays: usage of dual polarised arrays (yes or no).
    * LTE_params.ChanMod_config.winner_settings.TimeEvolution: usage of time evolution (yes or no).
    * LTE_params.ChanMod_config.winner_settings.PathLossModelUsed: usage of path loss model (yes or no).
    * LTE_params.ChanMod_config.winner_settings.ShadowingModelUsed: usage of shadow fading model (yes or no).
    * LTE_params.ChanMod_config.winner_settings.PathLossModel: path loss model function name (pathloss).
    * LTE_params.ChanMod_config.winner_settings.PathLossOption: Available options are CR_light, CR_heavy, RR_light, RR_heavy. CR=Corridor-Room, RR=Room-Room NLOS.
    * LTE_params.ChanMod_config.winner_settings.RandomSeed: sets a random seed. Can be left empty.
    * LTE_params.ChanMod_config.winner_settings.UseManualPropCondition: whether to use manual propagation condition (LOS/NLOS) settings or not (yes or no). If not, the propagation condition is drawn from probabilities.

F. Channel matrix source

- LTE_params.channel_matrix_source: Controls the generation of the channel matrix trace. generated to generate it every time. trace to load it from a trace.
- LTE_params.store_channel_trace: false, the storing of the channel trace it not yet fully implemented.
- LTE_params.channel_matrix_tracefile: filename of the trace file where the generated channel matrix trace is stored. Only applicable if trace mode is used (if the mode is set to trace, the channel matrix is already read from a trace, so it is meaningless to save it again in another trace).

G. Scheduler parameters

- LTE_params.scheduler.type: Currently there are four schedulers implemented
  - fixed: A scheduler that employs a fixed predefined schedule from LTE_params.scheduler.fixed_scheduler_assignm
  - fixed MU MIMO: A fixed scheduler for MU MIMO that schedules all users on the same time frequency resources.
  - max MU MIMO: A scheduler for MU MIMO that aims to maximize the sum throughput by exhaustive search over all possible user assignment combinations.
  - random MU MIMO: A scheduler for MU MIMO that randomly selects a subset of users to be scheduled.
  - greedy MU MIMO: A scheduler for MU MIMO that aims for high sum throughput by selecting user assignment combinations exploiting a greedy algorithm.
  - greedy MU MIMO: Similar to the
  - greedy MU MIMO scheduler, but picks users with the best Frobenius norm.
  - round robin: A round robin scheduler.
  - opt max Throughput: This scheduler selects the best possible schedule in terms of throughout by exhaustive search. (currently only for SISO)
  - approx max Throughput: This scheduler heuristically tries to maximize the throughput by a heuristic algorithm. (currently only for SISO)
  - best CQI: Scheduler that schedules users with the highest CQI values for a complete subframe.
- LTE_params.scheduler.fixed_scheduler_assignment: Defines the fixed schedule used when the fixed scheduler is selected. It is a column vector where the number of entries equals LTE_prams.nUE and each entry specifies how many resource blocks a UE is assigned. Therefore all entries of this vector must sum to the total number of resource blocks as defined by the simulation bandwidth LTE_params.Bandwidth.

VI. More Reference simulations

Besides the one mentioned on Section II, the simulator is provides two more reference simulations, which can be compared with the performance curves from 3GPP RAN documents such as [19] to cross-check the results of the simulator.

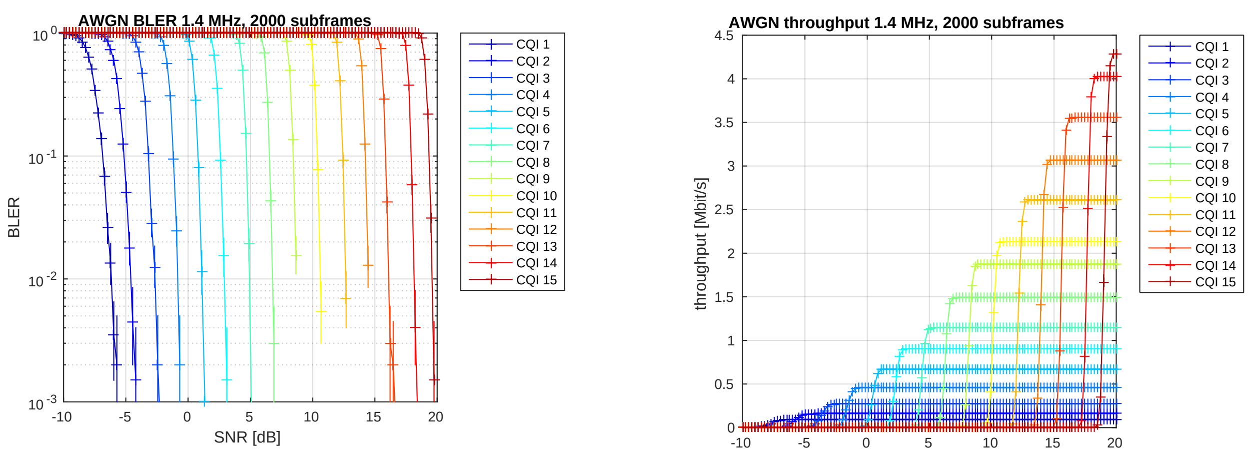
LTE_UL_LTE_UL_AWGN_test runs two simulation and produces throughput and Block Error Ratio (BLER) curves for each of them. The first simulation shows the results for the MCS defined in [8] (CQIs 1-15). The plots are shown in Figure 3. The second simulation runs with all the MCSs specified in R1-071967, page 16 [19] and the results are given in Figure 4.

The MCS, including the CQI value used in the simulator, the modulation and Effective Code Rate (ECR) used in each of the simulations are shown in Table II.

CQI	Modulation	ECR [19]	ECRx1024
101	4QAM	1/9	114
102	4QAM	1/6	171
103	4QAM	0.21	215
104	4QAM	1/4	256
105	4QAM	1/3	314
106	4QAM	0.42	430
107	4QAM	1/2	512
108	4QAM	0.58	594
109	4QAM	2/3	683
110	4QAM	0.73	748
111	16QAM	0.43	440
112	16QAM	0.46	471
113	16QAM	1/2	512
114	16QAM	0.54	553
115	16QAM	0.58	594
116	16QAM	0.61	625
117	16QAM	2/3	683
118	16QAM	0.73	748
119	16QAM	4/5	819
120	64QAM	0.58	594
121	64QAM	0.62	635
122	64QAM	2/3	683
123	64QAM	0.70	717
124	64QAM	0.74	758
125	64QAM	4/5	819
126	64QAM	0.85	870
127	64QAM	0.90	922

CQI	Modulation	ECR	ECRx1024 [8]
1	4QAM	0.0762	78
2	4QAM	0.1172	120
3	4QAM	0.1885	193
4	4QAM	0.3008	308
5	4QAM	0.4385	449
6	4QAM	0.5879	602
7	16QAM	0.3691	378
8	16QAM	0.4785	490
9	16QAM	0.6016	616
10	64QAM	0.4551	466
11	64QAM	0.5537	567
12	64QAM	0.6504	666
13	64QAM	0.7539	772
14	64QAM	0.8525	873
15	64QAM	0.9258	948

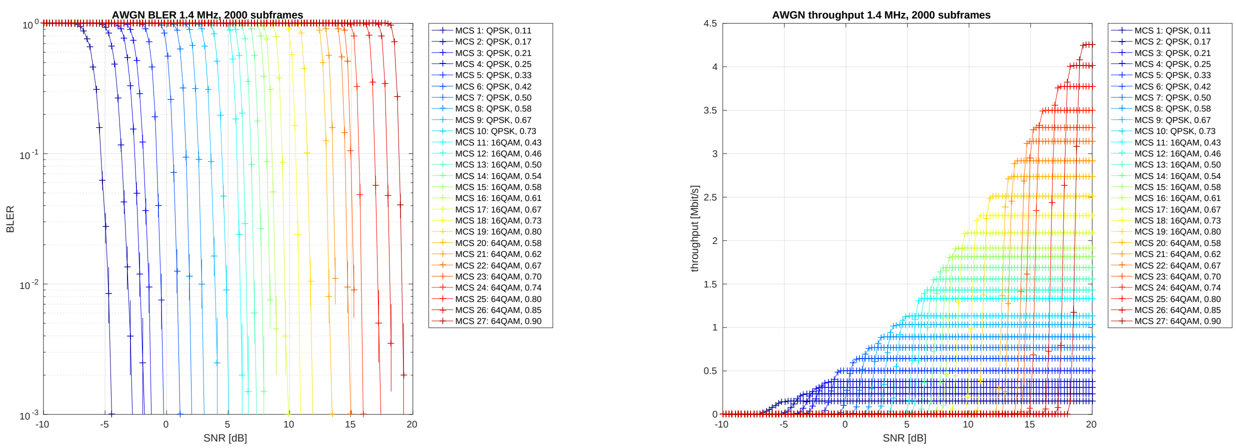
TABLE II: MCSs used in `LTE_UL_AWGN_test` for R1-07196 (left) and for LTE (right)



(a) BLER, AWGN no HARQ

(b) Throughput, AWGN, no HARQ

Fig. 3: Reference BLER and throughput plots for the 15 MCSs defined in [8]



(a) BLER, AWGN no HARQ

(b) Throughput, AWGN, no HARQ

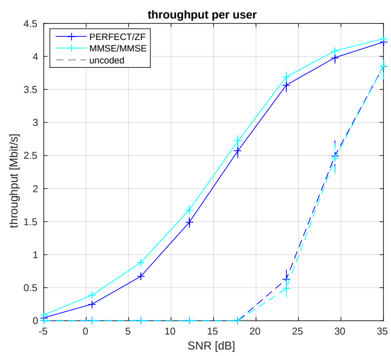
Fig. 4: Reference BLER and throughput plots for the 27 MCSs defined in [19]

VII. Running multiple simulations: multisim

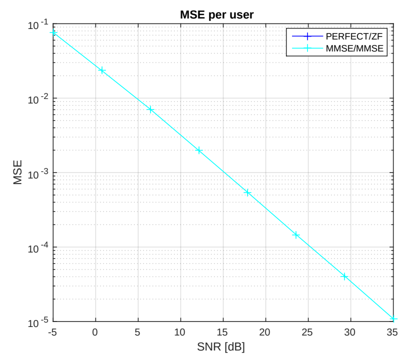
In Section II and Section IV we described how to run simulations using the simulator. This is the way to go if you want to evaluate the performance giving a single parameter set. In our experience it is often useful to quickly compare simulations for different parameter values.

A. Example

For this purpose we created a function called `multisim`. Figure 5 shows an example of the usage of `multisim`. In this example we compare two different simulations which use different estimation methods and equalizers We see that the MMSE receiver in combination with a MMSE equalizer outperforms the ZF receiver with perfect channel knowledge.



(a) comparison of throughput



(b) MSE for the MMSE estimation

Fig. 5: Example for using `multisim`

B. Usage

To benefit from `multisim` you need to know how to configure it. The function is called with a string pointing to a multisim config file which is in this example `simulation = multisim('multisim_config/multisim_doc_example')`. The config file used is shown on the right.

First you set elements of a (existing) class called `simulation` containing number of subframes and SNR values like in the normal batch file. As a parameter script it expects `LTE_UL_load_parameters` or a modified copy of it. This serves as your main simulation template. Then you create your subsimulations with `multisim.Config('Name')` which usually override some values of the `LTE_params` by using the `configs` add method. The first argument needs to be the parameter you want to change and the second is the value you want to change it to. It is possible to change an arbitrary number of parameters in each subsimulation. As a last step don't forget to add the subsimulations to the simulation class as shown in the example.
When multisim is called with this parameter file it will execute two consecutive simulations and pass all the subsimulations as a `simulation` class as the return value. The results are saved in `multisim_results` and can be plotted with `multisim.plot_simulation2(simulation)`.

```
%% config script for subsimulations
simulation.name = 'multisim_example';
simulation.parameter_scripts = {'...load_par...'};

% global settings
simulation.DEBUG_LEVEL = 1;
simulation.cqi_i = 1;
simulation.SNR_vec = linspace(-5,35,8);
simulation.N_subframes = 400;
simulation.show_plot = true;


%subsimulations
s1 = multisim.Config('PERFECT/ZF');
s1.add('BS_config.channel_estimation_method', 'PERFECT');
s1.add('BS_config.receiver', 'ZF');
simulation.add(s1);

s2 = multisim.Config('MMSE/MMSE');
s2.add('BS_config.channel_estimation_method', 'MMSE');
s2.add('BS_config.receiver', 'MMSE');
simulation.add(s2);
```

`multisim_doc_example.m`

VIII. Note on parallel simulations and random number generation

Note that when using parallel simulations the random number generator will return the same sequence of numbers in each of the parallel-running MATLAB labs. Since the `parfor` loop is over SNR values, this would mean that each SNR iteration is in principle identical to the other ones just with a different noise level (this may not be the case depending on the circumstances, though). If this is not adequate for your needs, you may need to modify the code regarding the `RandStream` initialization.

Below is a code that illustrates what happens when using `RandStreams` in parallel mode:

```
sim_length=15;
n_sims = 10;
output = zeros(n_sims,sim_length);
for sim_=1:n_sims
    a_RandStream = RandStream('mt19937ar','Seed',0);
    matlabpool open
    parfor t_=1:sim_length
        pause(1); %simulate doing something
        output(sim_,t_) = rand(a_RandStream);
    end
    matlabpool close
end
output
```

IX. Changelog

Changelog of the Vienna LTE-A Link Level Uplink simulator:

- v.1.6, 2016-09-11
  - add multi-user MIMO transmission mode 5
  - implementation of different schedulers for multi-user MIMO
  - channel estimation for multi-user MIMO transmissions added
  - support for the 3D channel model specified in TR 36.873
  - implementation of channel interpolation and prediction methods for time variant channels
  - enable simulations including inter-cell interference
  - implementation of an interference aware MMSE receiver for inter-cell interference
- v.1.5, 2015-15-12
  - support simulations with multiple base stations
  - support simulations with multiple users by means of scheduling
  - adapt the link adaptation and scheduling to the LTE-A Uplink structure
  - implement the feedback delay of the downlink channel
  - add MMSE channel estimation
  - enable receive diversity in transmission mode 1
  - various bugfixes
- v.1.4, 2015-12-06
  - support for fastfading simulations with a time variant channel
  - channel estimation for SISO and MIMO simulations
  - channel interpolation of the estimated channel for time variant channels
  - single user simulations only
  - improved link adaptation in case of ISI and ICI for MIMO transmission [20]
  - included Peak-to-Average Power Ratio (PAPR) calculation for performance evaluation
  - new script to plot multiple simulations
  - various bugfixes
- v.1.3r719,2014-26-05
  - CQI,PMI and RI Feedback are now available
  - Supported transmission modes are now according to the LTE-A standard; `single transmit antenna` and `CLSM`.
  - schedulers now support all possible bandwidths
  - CQI feedback clustering (granularity) is possible
  - feedback can take ISI and ICI caused by insufficient CP length into account
  - a new, more appropriate SINR averaging method (harmonic mean) can be used

- Plot function now supports confidence intervals.
- Additionally to normal Cyclic Prefix, extended CP length is now supported
- various bugfixes
- added reference simulations

X. Referencing

A version of the LTE-A Uplink Level Level Simulator paper is available in our publication data-base at `http://publik.tuwien.ac.at/files/PubDat_249398.pdf`.

If you are using the simulator for your scientific work, please use the refence below:

```
@article{zochmann2016exploring,
  title={Exploring the physical layer frontiers of cellular uplink},
  author={Z{\"o}chmann, Erich and Schwarz, Stefan and Pratschner, Stefan and Nagel, Lukas and Lerch, Martin and Rupp, Markus},
  journal={EURASIP Journal on Wireless Communications and Networking},
  volume={2016},
  number={1},
  pages={1},
  year={2016},
  publisher={Springer International Publishing}
}


Zoechmann, Erich, et al. "Exploring the physical layer frontiers of cellular uplink." EURASIP Journal
on Wireless Communications and Networking 2016.1 (2016): 1.
```

XI. Known issues

- The Long Term Evolution (LTE) simulators make use of the new Object-Oriented capabilities of Matlab (available since R2008a), the simulators will not run under older Matlab releases without extensive changes.
- Please note that MEX-files generated using Microsoft Visual C++ 2010 require that Microsoft Visual Studio 2008 run-time libraries be available on the computer they are run on. The runtime files can be downloaded for x86 or for x64.
- In order to be able to use the parallel version of the simulator (when setting `LTE_params.simulation_method` to `parallel`, you need the parallel toolbox (included by default with MATLAB r2009a and above or as an add-on with previous versions). It will not work if you don't have the toolbox, just crashing the moment the `matlabpool` function is called.
- In MATLAB versions prior to r2009a the code may not work, as the `commsrc.pn` function does not exist. You will need to replace every call to `commsrc.pn` with a call to `seqgen.pn` in order to run the simulator. No change in the arguments is needed. Such changes should be applied to the code in the `LTE_common_gen_Synchronization_Signal` and `LTE_common_gen_Reference_Signal` functions.
- In the `LTE_rx_turbo_decode` function, only the max-log-map decoder type has been tested. The `decoder_type` variable is used as input an configures the SISO decoder function, which is part of [21].
- It was pointed out that in [14], the phase ϕ is not different for each sinusoid. We are using a modified version [15].

XII. Using the WINNER Phase II channel model reference implementation

Starting with v.1.2r553, it is possible to use channels generated with the publicly-available MATLAB implementation of the WINNER Phase II Channel Model [22]. Since the code is distributed under the GNU GPL, its files are not included in the simulator release. In order to use to be able to use it, you will have to download it yourself. For this, go to the WINNER Phase II Model website, download the `WIM2_3D_ant_ver064_220908.zip` file and unzip the files in the `./Winner Channel Model` folder.

XIII. Using the 3D Channel Model from TR 36.873

Starting with v.1.6 the simulator supports the channel model based on three dimensional geometry as specified in TR 36.873 [23]. The code has been ported from the system level implementation published in [24]. The code for the model is distributed with the simulator and can be found in the `TR36873_3D_Model_standalone/` subdirectory.

To use this channel model in your simulations in `LTE_UL_load_parameters.m` set:

```
LTE_params.ChanMod_config.type = 'TR 36.873';
```

It is important to note that the large scale parameters in the model (delay spread, angular spreads, Ricean K factor) are generated once and used for all channel matrices over time. To get statistically meaningful results it is therefore necessary to perform multiple simulations with different random number seeds by either choosing different values for `LTE_params.channel_param_seed` for each simulation or by setting:

```
LTE_params.random_channel_param_seeding = false;
```

Both settings can be found in LTE_UL_load_params.m.

Specific parameters for the model can be set in the same file LTE_UL_load_parameters.m. They are:

- LTE_params.TR_36_873.pathloss_enabled: Activates (true) or deactivates (false) the pathloss model.
- LTE_params.TR_36_873.environment: Sets the simulation scenario to Urban Macro ('UMa') or Urban Micro ('UMi').
- LTE_params.TR_36_873.LOS_according_model: Sets the propagation condition (LOS/NLOS) for the connections according to the probabilities defined by the model (true) or specifies the condition to be hard coded by LTE_params.TR_36_873.UE_is_LOS (false).
- LTE_params.TR_36_873.indoor_according_model: Sets the position of the UEs (indoor/outdoor) according to the probabilities defined by the model (true) or specifies the condition to be hard coded by LTE_params.TR_36_873.UE_is_indoor (false).
- LTE_params.TR_36_873.UE_is_LOS: Sets the propagation condition for each link to either LOS (true) or NLOS (false). The setting only takes effect if LTE_params.TR_36_873.LOS_according_model is true. it's size is [LTE_params.nBS, LTE_params.nBS*LTE_params.nUE].
- LTE_params.TR_36_873.UE_is_indoor: Determines if each UE is indoors (true) or outdoors (false). The parameter only takes effect if LTE_params.TR_36_873.indoor_according_model is true. It's size is [1, LTE_params.nBS*LTE_params.nUE].
- LTE_params.TR_36_873.UE_dist_indoor: Determines each link's distance between eNodeB and UE that proceeds indoors. The setting only takes effect if LTE_params.TR_36_873.indoor_according_model is true. It's unit is meters and it's size is [LTE_params.nBS, LTE_params.nBS*LTE_params.nUE]
- LTE_params.TR_36_873.map_resolution: Defines the resolution of the maps for spatial correlation of large scale parameters. It's unit is meters/pixel.
- LTE_params.TR_36_873.eNodeB_hex_grid: Places the eNodeBs in a hexagonal grid separated by the inter-site distance defined by the selected scenario (UMi or UMa) (true) or places the eNodeBs at the positions defined by LTE_params.TR_36_873.eNodeB_pos (false).
- LTE_params.TR_36_873.UE_pos_rand: Places the UEs randomly inside circle around eNodeB (true) or places the UEs at hard-coded positions defined by LTE_params.TR_36_873.UE_pos (false).
- LTE_params.TR_36_873.eNodeB_pos: Defines the positions of the eNodeBs. Only takes effect if LTE_params.TR_36_873.eNodeB_hex_grid is false. It's size is [LTE_params.nBS, 2] and it's unit is meters.
- LTE_params.TR_36_873.UE_pos: Defines the positions of the UEs. Only takes effect if LTE_params.TR_36_873.UE_pos_rand is false. It's size is size [LTE_params.nBS*LTE_params.nUE, 2] and it's unit is meters.
- LTE_params.TR_36_873.antenna_azimuth_offset: Sets the azimuth offset of each eNodeBs' antennas in degrees. It's unit is degrees and it's size is [1, LTE_params.nBS].
- LTE_params.TR_36_873.UE_heights_according_to_model: Determines if the UE heights are set according to the model (true) or to the values specified in LTE_params.TR_36_873.UE_heights (false).
- LTE_params.TR_36_873.eNodeB_heights_according_to_model: Determines if the eNodeB heights are set according to the model (true) or to the values specified in LTE_params.TR_36_873.eNodeB_heights (false).
- LTE_params.TR_36_873.UE_heights: Sets the height of the UEs in meters, it's size is [1, LTE_params.nBS*LTE_params.nUE]. This setting only takes effect if LTE_params.TR_36_873.UE_heights_according_to_model is true.
- LTE_params.TR_36_873.eNodeB_heights: Sets the height of the eNodeBs in meters, it's size is [1, LTE_params.nBS]. This setting only takes effect if LTE_params.TR_36_873.eNodeB_heights_according_to_model is true.
- LTE_params.TR_36_873.UE_antenna_polarization: Sets the antenna polarizations at the UEs to either cross-polarized ('XPOL') or linearly polarized ('ULA').
- LTE_params.TR_36_873.UE_antenna_element_horizontal_spacing: Sets the spacing between antenna elements of the UEs in the horizontal domain, in multiples of the wavelength.
- LTE_params.TR_36_873.antenna.antenna_gain_pattern: Sets the antenna gain pattern at the eNodeB to either as specified in the model ('TR36.873 3D antenna') or to a omni-directional pattern ('TR36.873 3D antenna omnidirectional').
- LTE_params.TR_36_873.antenna.antenna_polarization: Sets the antenna polarizations at the eNodeB to either cross-polarized ('XPOL') or linearly polarized ('ULA').
- LTE_params.TR_36_873.antenna_element_vertical_spacing: Sets the spacing between antenna elements of the eNodeB in the vertical dimension (i.e. between rows), in multiples of the wavelength.
- LTE_params.TR_36_873.antenna_element_horizontal_spacing: Sets the spacing between antenna ele-

ments in the horizontal dimension (i.e. between columns), in multiples of the wavelength.

- `LTE_params.TR_36_873.nr_of_antenna_elements_in_each_column`: Sets the number of antenna elements in each column of the eNodeB.
- `LTE_params.TR_36_873.electrical_downtilt`: Sets the electrical downtilt angle of the eNodeB antennas, in degrees.
- `LTE_params.TR_36_873.mechanical_downtilt`: Sets the mechanical downtilt angle of the eNodeB antennas, in degrees.
- `LTE_params.TR_36_873.mechanical_slant`: Sets the mechanical slant angle of the eNodeB antennas, in degrees.
- `LTE_params.TR_36_873.antenna.max_antenna_gain`: Sets the maximum antenna gain of the eNodeB antennas in dBi, default value is 8 dBi.

XIV. Questions

For questions please check our *forum* at `https://www.nt.tuwien.ac.at/research/mobile-communications/forums/` , where you will be able to post your questions/comments/bug reports. It makes it easier for you to see what other people asked and also makes it easier for us to answer you (when we have time).

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XVI. The People (so far) behind the development of the simulator

- Markus Rupp
- Stefan Schwarz
- Michal Šimko
- Günther Mader
- Victor Sen Abad
- Stefan Pratschner
- Erich Zöchmann
- Lukas Nagel
- Markus Gasser

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- Hash calculation in the `utils.hashing` class. The `DataHash` function provides MD5/SHA1 hash functionality and is under the BSD license [25]. The license agreement for the `DataHash` code is found in the `documentation/` folder. The code was retrieved from the Matlab File Exchange on 27.04.2012 [26].

XVIII. Acknowledgment

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