Vienna LTE Simulators
Link Level Simulator Documentation, v1.7r1089

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Abstract

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

I. FOREWORD

The LTE 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 Markus Rupp, or Josep Colom Ikuno.

The detailed license agreement for the LTE 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 [3], and the MIT License [4].

II. RUNNING THE SIMULATOR FOR THE FIRST TIME

The LTE Link Level simulator simulator is provided with a test simulation scenario that can be used to verify that the simulator runs in the expected way.

In the main directory you can execute the `LTE_sim_batch_quick_test` MATLAB script. This script provides a means to test the performance of an LTE transmission on an uncorrelated PedB channel and flat Rayleigh channel for several transmission modes [5]. Since currently the feedback calculation for the Closed Loop Spatial Multiplexing (CLSM) mode is not implemented, only the Single-Input Single-Output (SISO), Transmission Diversity (TxD) and Open Loop Spatial Multiplexing (OLSM) modes are simulated.

The result of the simulation is a group of result files that is stored in the `./results` folder. The `plots_quick_test_results` MATLAB script provides the means of plotting the results for this specific simulation. By executing the script without any change, the Block Error Ratio (BLER) and throughput results for the following simulations are shown:

- 5000 Transmission Time Interval (TTI) long, flat Rayleigh channel, no retransmissions: Figures 1(a) and 1(c).
- 5000 TTI long, flat Rayleigh channel, maximum of three retransmissions: Figures 1(b) and 1(d).
- 5000 TTI long, uncorrelated PedB channel, no retransmissions: Figures 2(a) and 2(c).
- 5000 TTI long, uncorrelated PedB channel, maximum of three retransmissions: Figures 2(b) and 2(d).

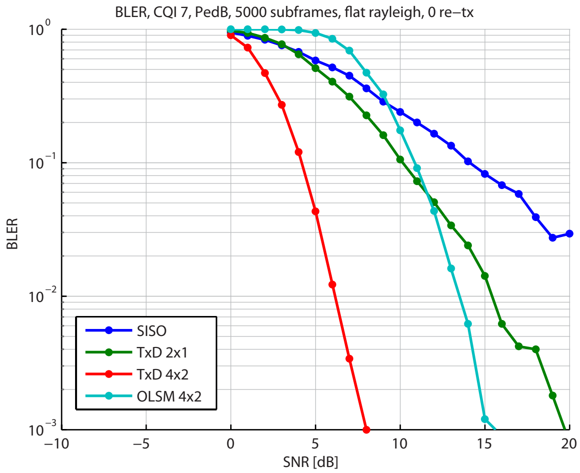
The figures obtained by running `LTE_sim_batch_quick_test` and the ones shown in Figures 1 and 2 should match.

The settings used in the `LTE_sim_batch_quick_test` MATLAB script can be found in Table I, although a more detailed description can be found in Section V and the `LTE_load_parameters_SUSISO_quick_test` (SISO mode) and `LTE_load_parameters_SUMIMO_quick_test` (MIMO modes) configurations files.

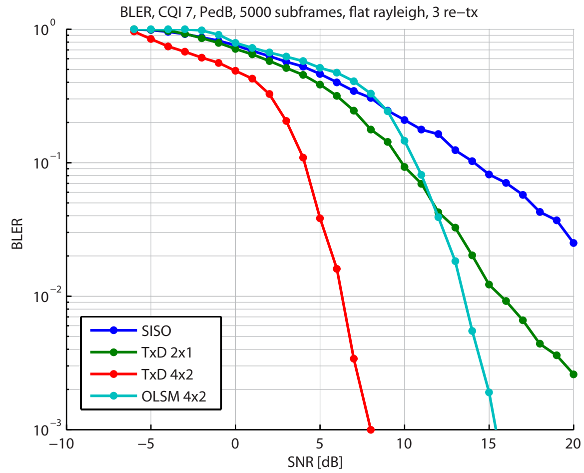
III. MEX FILES

Computation-intensive parts of the LTE 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 not that some of the functions there are licensed under other license terms. Please check Section XVII for more details.

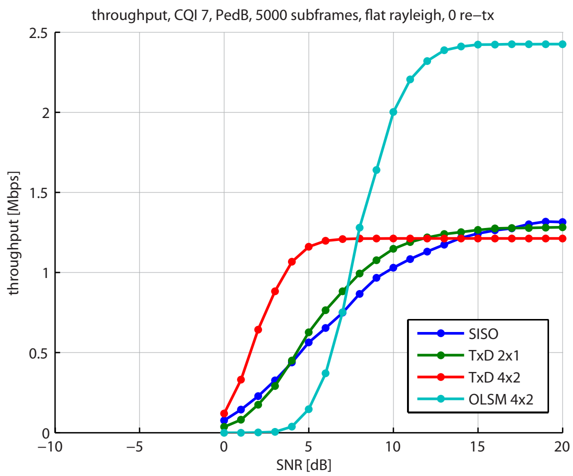
The MEX files distributed with the simulator release are the Windows 64-bit version. Should you require them for any other platform you recompile them by using the `LTE_aux_mex_files` script. You can find more information on how to use/write/compile MEX files here.



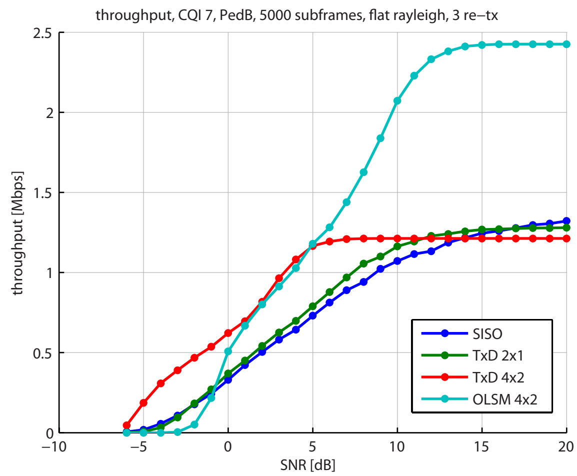
(a) BLER, flat Rayleigh channel, no HARQ



(b) BLER, flat Rayleigh channel, 3 retransmissions



(c) Throughput, flat Rayleigh channel, no HARQ



(d) Throughput, flat Rayleigh channel, 3 retransmissions

Fig. 1. Plots resulting from running the `LTE_sim_batch_quick_test.m` MATLAB script (flat rayleigh)

Parameter	Value
Number of User Equipments (UEs)	1
Bandwidth	1.4 MHz
Retransmissions	0 and 3
Channel type	Flat Rayleigh, PedB uncorrelated
Filtering	Block Fading
Receiver type	Soft Sphere Decoder
Simulation length	5000 subframes
Transmit modes	SISO, TxD (2x1 and 4x2) and OLSM (4x2)

TABLE I
BASIC SETTINGS USED FOR THE `LTE_SIM_BATCH_QUICK_TEST.M` MATLAB SCRIPT

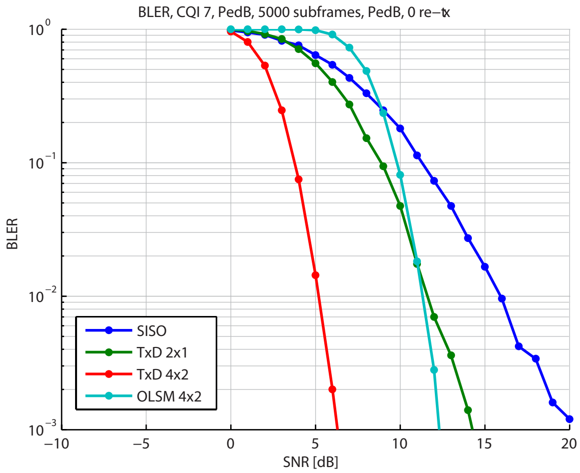
IV. RUNNING YOUR OWN SIMULATIONS

While the `LTE_sim_batch_quick_test` is adequate to get familiar with the basic structure of the simulation script necessary to run it, you may need more flexibility than the one offered with the quick test script.

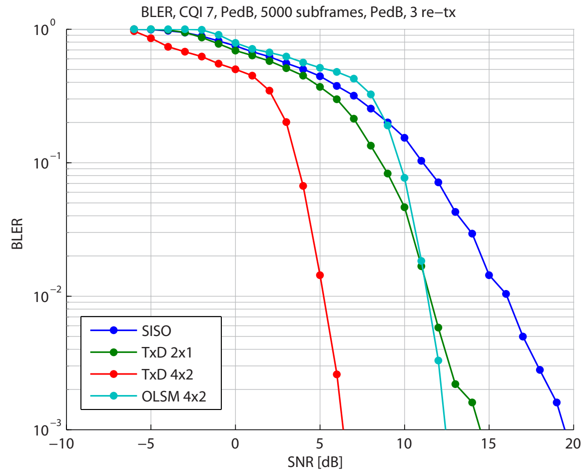
For this, you can check the `LTE_sim_batch.m` script. It provides the means to run a simulation for a specific set of Modulation and Coding Schemes (MCSs).

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

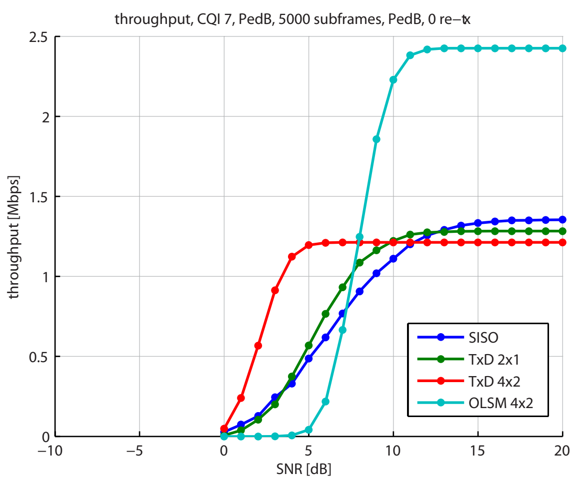
- `cqi_i`: set of MCSs that are used for the simulation. In [6], 15 different Channel Quality Indicators (CQIs) are specified, denominated CQIs. If you want to simulate for all possible CQIs, just set `cqi_i` to be `[1:15]`. Analogously, in the MATLAB notation, for a simulation for CQIs 1 and 7 that would be `[1 7]`.



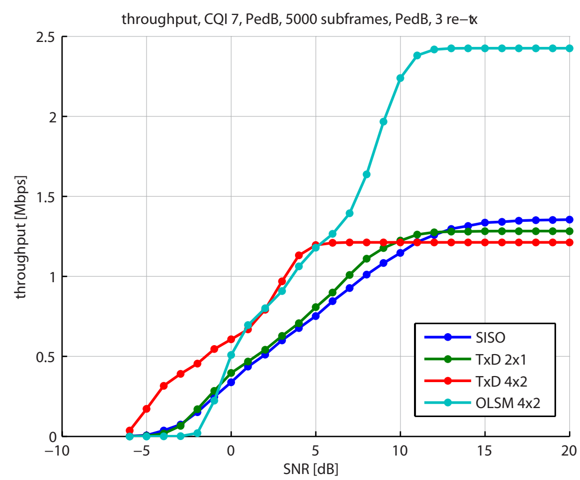
(a) BLER, PedB channel, no HARQ



(b) BLER, PedB channel, 3 retransmissions



(c) Throughput, PedB channel, no HARQ



(d) Throughput, PedB channel, 3 retransmissions

Fig. 2. Plots resulting from running the `LTE_sim_batch_quick_test.m` MATLAB script (PedB)

- `N_subframes`: the length of the simulation, or how many subframes (TTIs) are simulated.
- `SNR_vec`: a vector containing the Signal to Noise Ratios (SNRs) that will be used for each simulation run. Use an SNR range adequate to the CQI that you are simulating. The vectors set in the script are adequate for a SISO Additive White Gaussian Noise (AWGN) simulation. See Section VIII for a more detailed description of how SNR is defined.
- `LTE_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. Four basic preconfigured options are given that can be directly used by appropriately setting the `LTE_params.Simulation_type` variable accordingly, thus skipping the configuration of the rest of the parameters. See Section VII if you want to use the parameter file to reproduce the results/plots from a paper.
  - `SUSISO`: Single-user SISO simulation
  - `MUSISO`: Multi-user (preconfigured to two users) SISO simulation
  - `SUMIMO`: Single-user Multiple-Input Multiple-Output (MIMO) simulation
  - `MUMIMO`: Multi-user (two users) MIMO simulation
- `LTE_sim_main`: main routine of the simulator, also called by the `LTE_sim_batch_XXX` files.
- 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 the `LTE_config` file:

A. General parameters

- LTE_params.nUE: number of UEs to simulate.
- LTE_params.nBS: number of eNodeBs (cells) that will be simulated. Do not change this parameter, as support for multiple eNodeBs is not yet implemented.
- LTE_params.uplink_delay: the delay the uplink experiences. It applies to ACKnowledgments (ACKs), CQI, Precoding Matrix Indicator (PMI) and Rank Indicator (RI) reports. An integer number ≥ 0. Useful if you want to experiment with scheduling algorithms or feedback strategies.
- LTE_params.show_plots: whether plots are shown during the simulation or not.
- LTE_params.trace_subcarrier_SNR: if set to true, a trace of the subcarrier SNRs is generated and stored in the simulation_results object.
- LTE_params.N_seed_reset: resets the random number generator seeds to a new value after LTE_params.N_seed_reset subframes. This is used for the case where a time-correlated channel is generated (modified Rosa Zheng model [7], [8]). When low speed channels are evaluated, a too-long simulation would be needed in order to obtain statistically meaningful results. Thus, to avoid such situations, the channel can be "reset" to a new seed every N subframes.
- LTE_params.carrier_freq: 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.
- 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. Valid values are 0, 1, 2 or 3. Higher numbers will give you an error, as the rate matching is not defined for retransmission numbers (rv_idx) higher than 3.
- LTE_params.SubcarrierSpacing: in Hz, 15 kHz, a 7.5 kHz subcarrier spacing is also possible (just for MBSFN-based multicast/broadcast transmissions). Tests were so far performed using a 15 kHz spacing, so the 7.5 kHz spacing is not thoroughly tested.
- LTE_params.CyclicPrefix: cyclic prefix length [10]. Either normal or extended for MBSFN-based multicast/broadcast transmissions.
- LTE_params.simulation_type: 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 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).
- LTE_params.introduce_frequency_offset: whether you want a frequency offset to be introduced. Frequency offset introduction and correction are currently under development, so for now this option may not yet be fully functional. Further carrier offset options are also present in the UE parameters configuration Section V-C.
- 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.usePBCH: whether space for the physical broadcast channel is reserved inside the resource grid (no data is transmitted on these resource elements).
- LTE_params.usePDCCH: whether space for the physical downlink control channel is reserved inside the resource grid.
- LTE_params.trafficmodel.usetraffic_model: whether users generate traffic according to prespecified traffic models (RAN R1-070674) or a full buffer situation is assumed. Currently the traffic models are not used in the simulations (only full buffer is possible).

B. 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: Set to true or false. If mode is generated, the channel trace will be saved at the end of the simulation.
- 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).

C. UE, eNodeB and UE feedback specific parameters

- `LTE_params.UE_config.LLR_clipping`: specifies the LLR clipping level.
- `LTE_params.UE_config.turbo_iterations`: Number of iterations of the turbo decoder. Set by default to 8.
- `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 [11]).
- `LTE_params.UE_config.channel_estimation_method`: Currently the following channel estimators are available: `PERFECT`, `LS`, or `MMSE`.
- `LTE_params.UE_config.channel_interpolation_method`: `linear`, `cubic`, `spline`, `sinc_freq`, `sinc_time`, or `T-F`. For fast fading, `linear`, `cubic`, and `v4` are available.
- `LTE_params.UE_config.autocorrelation_matrix_type`: type of autocorrelation matrix. Either `ideal` or `estimated`.
- `LTE_params.UE_config.user_speed`: channel speed (m/s).
- `LTE_params.UE_config.realization_num`: number of channel realizations. Used for averaging to obtain the channel autocorrelation matrix.
- `LTE_params.UE_config.realization_num_total`: first xy number of channel realizations are used just for the estimation of the autocorrelation matrix.
- `LTE_params.UE_config.CDD`: Cyclic Delay diversity
  - 0: zero delay CDD (3GPP TS 36.211-820 Section 6.3.4.2.1 [10], page 37)
  - 1: small delay CDD (3GPP TS 36.211-820 Section 6.3.4.2.1 [10], page 37). Although in the newest standard version this is not defined anymore
  - 2: large delay CDD (3GPP TS 36.211-820 Section 6.3.4.2.2 [10], page 38)
- `LTE_params.UE_config.mode`: the transmission modes are defined in TS 36.213-820 Section 7.1, page 12 [6] and are:
  - 1: single antenna.
  - 2: TxD.
  - 3: OLSM.
  - 4: CLSM.
  - 5: Multiuser MIMO (not yet implemented)
- `LTE_params.UE_config.nRX`: number of receive antennas at the UE.
- `LTE_params.UE_config.carrier_freq_offset`: carrier frequency offset normalized to subcarrier spacing (not yet implemented).
- `LTE_params.UE_config.perfect_freq_sync`: whether the UE is perfectly synchronized in frequency.
- `LTE_params.UE_config.rfo_correct_method`: receiver frequency offset correction method. Either `none`, `subframe`, or `FIR`. Not yet implemented.
- `LTE_params.UE_config.receiver`: either `SSD` for a Soft Sphere Decoder, `ZF` for a Zero Forcing (ZF) receiver and `MMSE` for a Minimum Mean Square Error (MMSE) receiver.
- `LTE_params.UE_config.PMI_fb_granularity`: granularity of PMI feedback in multiples of resource blocks
- `LTE_params.UE_config.CQI_fb_granularity`: granularity of CQI feedback in multiples of resource blocks
- `LTE_params.UE_config.PMI_fb`: whether PMI feedback is activated or not (true/false)
- `LTE_params.UE_config.RIandPMI_fb`: whether RI feedback is activated in addition to PMI feedback (true/false)
- `LTE_params.UE_config.CQI_fb`: whether CQI feedback is activated
- `LTE_params.UE_config.predict`: whether channel prediction is activated for the feedback calculation; the channel prediction algorithm is simple linear extrapolation on every subcarrier;
- `LTE_params.UE_config.SINR_averaging.averager`: defines the Effective Signal to Interference and Noise Ratio Mapping (ESM) averager used. Possible values are `EESM` and `MIESM`.
- `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 behaviour, as the calibration factors (EESMbetas and MIESMbetas) are not trained for other MCSs.
- `LTE_params.BS_config.nTx`: number of antennas at the eNodeB.
- `LTE_params.feedback.ignore_channel_estimation`: whether the channel estimation mean square error is taken into account during the feedback calculation (as additional noise) or not
- `LTE_params.feedback.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 4×4 systems this degrades the performance of the feedback method.

D. Channel model parameters

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

- `LTE_params.ChanMod_config.filtering`: `BlockFading` (channel is constant during one subframe) or `FastFading`.
- `LTE_params.ChanMod_config.interpolation_method`: the channel interpolation method for the channels which are generated 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 [7], [8].
- `LTE_params.ChanMod_config.type`: specifies the type of channel used. The available ones are:
  - `AWGN`: Additive White Gaussian Noise channel.
  - `flat Rayleigh`: flat Rayleight channel.
  - Tap-delay based models: `PedA`, `PedB`, `PedBcorr`, `VehA`, `VehB`, `TU`, `RA`, and `HT` [12], [13].
  - Externally-generated channel coefficients: `winner_II`. Uses the publicly-availabe Winner II implementation to generate the channel coefficients [14]. 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.
- `LTE_params.ChanMod_config.corr_coefRX`: correlation between the receiver antennas. Only compatible with block fading filtering.
- `LTE_params.ChanMod_config.corr_coefTX`: correlation between the transmitter antennas. Only compatible with block fading filtering.
- `LTE_params.ChanMod_config.time_correlation`: sets whether the channel realizations are time-correlated or not. `correlated` or `independent`. This parameter is also related with `LTE_params.N_seed_reset`.

E. Scheduler parameters

Configuration of the scheduler parameters.

- `LTE_params.scheduler.type`: type of scheduler. Either `round robin`, `best cqi`, or `fixed`.

- `LTE_params.scheduler.assignment`: either `static`, `semi static` or `dynamic`. Whether the scheduler will statically assign or dynamically assign CQIs and other params. The `best cqi` scheduler is capable of assigning MCSs dynamically. The semi static scheduler adapts automatically the precoder and layer number according to the PMI and RI feedback (use this one in conjunction with closed loop spatial multiplexing and activated PMI and RI feedback). The semi static scheduler assigns resource blocks in a round robin fashion.
- `LTE_params.scheduler.fixed_scheduler_assignment`: this option is used only for the `fixed` scheduler. In that case, the parameter is a vector of length `LTE_params.nUE` containing the number of RBs allocated to each user. The total number or assigned RBs must be equal or less than the number of RB available in the specified bandwidth: eg. for 2 UEs and 1.4 MHz `[4 2]` would assign four RBs to the first user and two to the second.
- `LTE_params.scheduler.cqi`: the CQI the scheduler is going to use when transmitting data. When set to `'set'`, when in the `static` case, the CQI value to use will be read from the `cqi_i` variable, which is to be set from the script file that launches the simulation (eg. `LTE_sim_batch`).
- `LTE_params.scheduler.PMI`: sets the Precoding Matrix Indicator feedback for the CLSM transmit mode.

VI. REFERENCE SIMULATION RESULTS INCLUDED

Besides the one mentioned on Section II, the simulator is provided with some reference simulation results, which can be compared with performance curves from 3GPP RAN documents such as [15] to cross-check the results of the simulator.

The example simulation results distributed with the simulator are described below.

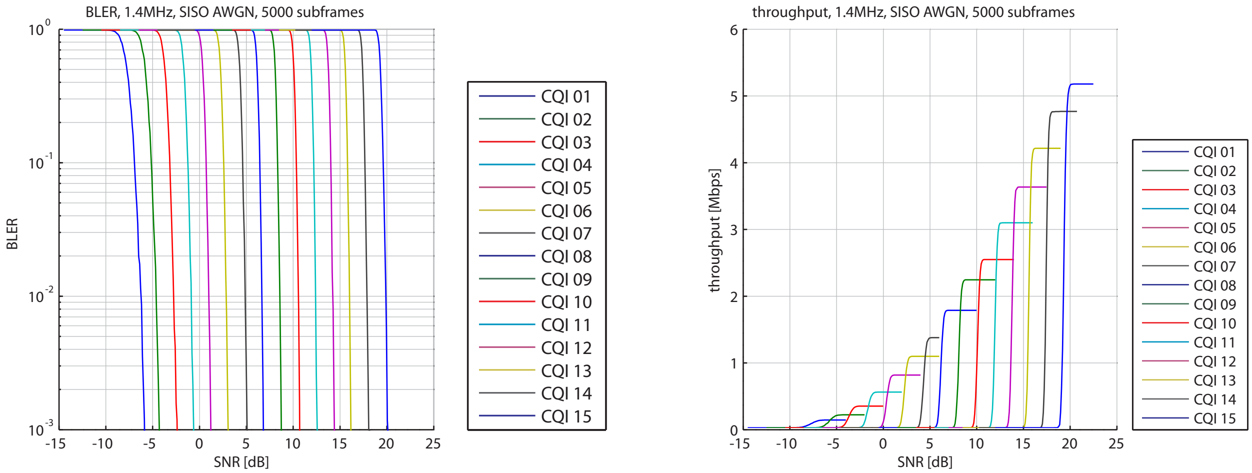
- `plot_reference_BLER_curves_r548` shows the plots in Figure 3, showing BLER and throughput for an AWGN simulation using the MCS defined in [6] (CQIs 1-15).
- `plot_R1071967_throughput_curves_r553` shows the BLER and throughput curves obtained from performing AWGN simulations with the MCSs specified in R1-071967, page 16 [15], as seen 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 [15]	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 [6]
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

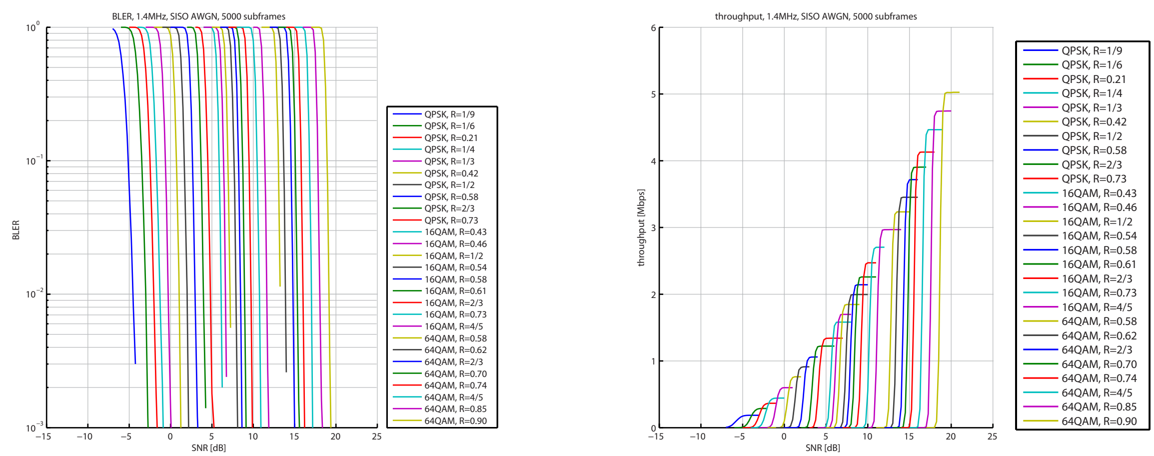
TABLE II
MCSS USED IN THE `LTE_SIM_BATCH_R1_07196` (LEFT) AND `LTE_SIM_BATCH_QUICK_TEST` (RIGHT) MATLAB SCRIPTS



(a) BLER, AWGN no HARQ

(b) Throughput, AWGN, no HARQ

Fig. 3. Reference BLER and throughput plots for the 15 MCSs defined in [6]



(a) BLER, AWGN no HARQ

(b) Throughput, AWGN, no HARQ

Fig. 4. Reference BLER and throughput plots for the 27 MCSs defined in [15]

VII. Reproducing the results/plots presented on a paper

One of the main points of the simulator is to allow you to reproduce and review our results, as well as the algorithms that produce them. For each of the following publications a script is prepared in the folder *paper scripts* that will reproduce the results in the corresponding paper:

- M. Šimko, C. Mehlführer, M. Wrulich, and M. Rupp, "Doubly Dispersive Channel Estimation with Scalable Complexity", in Proc. WSA 2010, Bremen, Germany, Feb. 2010 [16]:
  `LTE_sim_batch_michal_wsa_2010.m'`
- S. Schwarz, M. Wrulich, and M. Rupp, "Mutual information based calculation of the precoding matrix indicator for 3GPP UMTS/LTE", in Proc. WSA 2010, Bremen, Germany, Feb. 2010 [17]:
  `LTE_sim_batch_schwarz_wsa_2010.m'`
- S. Schwarz, C. Mehlführer, and M. Rupp, "Calculation of the Spatial Preprocessing and Link Adaption Feedback for 3GPP UMTS/LTE", in Proc.Wireless Advanced2010, London, Great Britain, June 2010 [18]:
  `LTE_sim_batch_schwarz_WiAd_2010.m'`

VIII. SNR definition

In a MIMO-Orthogonal Frequency Division Multiplexing (OFDM) transmission system the SNR γ is the measurement for channel quality information and is a key factor of link error prediction. There are different measures or calculation procedures for the SNR in SISO and MIMO systems. For SISO systems the SNR can be viewed as receiving SNR, that is, received signal-to-noise ratio before the detector. Usually post-detection Signal to Interference and Noise Ratio (SINR) is used for MIMO link prediction. It is representing the SNR after combining in the receiver and measures the likelihood that a MCS will be decoded successfully.

The LTE Link Level simulator SNR γ is defined as follows:

- `BS_output.y_tx` contains the Tx-signal vector $\mathbf{x} = [\mathrm{x}_1, \ldots, \mathrm{x}_{N_\mathrm{T}}]^\mathrm{T} \in \mathbb{C}^{N_\mathrm{T} \times 1}$, where $\mathrm{x_k} \in \mathbb{C}$ with $\mathrm{k} \in [1, \ldots, N_\mathrm{T}]$ is the Tx-symbol sent from the k-th Tx-antenna ($N_\mathrm{T} \ldots$ number of Tx-antennas). We get
  - the total Tx-power, $\sigma_\mathrm{x}^2 = \mathrm{trace}(\mathbf{R}_\mathrm{x}) = \mathrm{trace}(\mathrm{E}\left\{\mathbf{x}\mathbf{x}^\mathrm{H}\right\}) = 1$
  - the Tx-power per Tx-antenna, $\sigma_{\mathrm{x_k}}^2 = \mathrm{E}\{|\mathrm{x}_k|^2\} = 1/N_\mathrm{T}$
- `ChanMod_output.H` defines the channel matrix $\mathbf{H}$, with $\|\mathbf{H}\|_\mathrm{F}^2 = N_\mathrm{T} N_\mathrm{R}$ ($N_\mathrm{R} \ldots$ number of Rx-antennas)
- `BS_output.cell_genie.v` defines the noise vector $\mathbf{v}$ with respect to the size of the Fast Fourier Transform (FFT) (`LTE_params.Nfft`) and the number of subcarriers (`LTE_params.N_tot`) before the detector, where $vec(\mathbf{v}) \sim \mathcal{CN}(\mathbf{0}, \sigma_\mathrm{v}^2\mathbf{I})$
- `BS_output.cell_genie.n` defines the noise vector $\mathbf{n}$ after the FFT, where $vec(\mathbf{n}) \sim \mathcal{CN}(\mathbf{0}, \sigma_\mathrm{n}^2\mathbf{I})$
- `ChanMod_output.y_rx` contains the Rx-signal vector $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{v}$
  - we get the receive SNR (before the detector),

$$\gamma_\mathrm{prefft} = \frac{\|\mathbf{H}\mathbf{x}\|_\mathrm{F}^2}{N_\mathrm{R}\sigma_\mathrm{v}^2} = \frac{N_\mathrm{R}}{N_\mathrm{R}\sigma_\mathrm{v}^2} = \frac{1}{\sigma_\mathrm{v}^2}$$

  - where the SNR after the FFT becomes,

$$\gamma_\mathrm{postfft} = \frac{\|\mathbf{H}\mathbf{x}\|_\mathrm{F}^2}{N_\mathrm{R}\sigma_\mathrm{n}^2} = \frac{N_\mathrm{R}}{N_\mathrm{R}\sigma_\mathrm{n}^2} = \frac{1}{\sigma_\mathrm{n}^2}$$

  The difference between γ_prefft and γ_postfft is given by the relation $\sigma_\mathrm{v}^2/\sigma_\mathrm{n}^2 = N_\mathrm{fft}/N_\mathrm{tot}$ (using a FFT-size of 128 and 72 subcarrriers, we get $N_\mathrm{fft}/N_\mathrm{tot} = 128/72 = 1.778 \triangleq 2.5\,dB$).
  We recommend to use the SNR after FFT (γ_postfft) when doing simulations over SNR, as this allows direct comparisons to theoretic results.

IX. 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
```

X. Changelog

- v.1.7r1089, 2011-10-04
  - Added possibility to adjust power radiated at the pilot symbol positions.
  - MEX files are now compiled with Microsoft Visual C++ 2010, so the appropriate runtime files are needed. Refer to Section XII for more information on how to get them.
  - Fixed typos in the `LTE_sim_batch_BLER_curves` file that reproduces the AWGN BLER curves.

  - BICM capacity curves are now loaded by default not from a file, but from a hardcoded source. Loading from a file is still supported, though.
  - Fixed error in the rate matching that caused an incorrect number of bits than otherwise expected by the layers for cases of bandwidth higher than 1.4 MHz and certain resource block allocations.
  - Changed the layout of the `load_parameters` file. It was getting so long it was no longer readable. Moved the individual configuration parameters for each simulation type to separate object files in the `simulation_config` package.
  - Fixed discrepancy initialization in the gold code generation MEX file. Thanks to Srikanth Isanaka for pointing out this bug and Mitsuo Sakamoto for generously providing an updated version of the gold code generation code.
- v.1.6r917, 2011-01-19
  - Fixed error in `LTE_sim_results_plots` when there is no frequency offsett estimation.
  - Fixed signaling bug for TB sizes smaller than 40 bits. Thanks to Wang Dongming (Southeast University, China) for pointing out this bug.
  - Fixed bug in the new implementation of the rate matching. The LLR repetition was not taken into account, therefore affecting performance.
- v.1.5r811, 2010-11-05
  - Added experimental multi-base station simulation support. Still in very early development stages.
  - Reimplementation in MATLAB of most of the rate-matching procedures. The code is optimized enough so that MEX functions are now much less needed. This should improve code readability and maintainability.
  - Added "Companies (no matter profit-oriented or not) are not allowed for free usage and have to contact the licensor before usage." to the license agreement (Section A).
  - Fixed bug in the fixed scheduler. The `PBCHsyms` variable was being used, thus causing the simulation to crash when the scheduler function was called.
  - The CQI used for each Transport Block (TB) transmission in now stored in the results trace (`used_CQI` variable in `ueSpecificTraces`, in turn stored in `simulation_results`).
  - Added trace to track the codeblock BLER. The ACK value is the decimal representation of the codeblock ACK vector for each codeword.
- v.1.4r715, 2010-07-12
  - Fixed bug in the channel coding process. According to [9]: "If the code to be encoded is the 0-th code block and the number of filler bits is greater than zero, i.e. $F > 0$, then the encoder shall set $c_k = 0, k = 0, \ldots, (F-1)$ at its input and shall set d_k^0 =`<NULL>`, $k = 0, \ldots, (F-1)$ and d_k^1 =`<NULL>`, $k = 0, \ldots, (F-1)$ at its output". These bits were erroneously set to 0 instead of `<NULL>`. In `LTE_rx_DLSCH`, the first `BS_signaling.TB_segmentation.F` LLR values of $d^{(0)}$ and $d^{(1)}$ are replaced by `-LTE_params.UE_config.LLR_clipping`. Thanks to Wu Gaojin (University of Posts and Telecommunications, China) for pointing out this bug.
  - Fixed bug in the RX rate matching process that caused a crash when no filler (`<NULL>`) bits were present (ie. `UE_signaling.turbo_rate_matcher(stream_index).null_positions{i}` was empty). Thanks to Narciso García Cano (Universidad Politécnica de Madrid, Spain) for helping us out with this bug.
  - The Gold sequence generation was based on version 8.2.0 of the standard. Between the latest release and v8.2.0., pseudo random sequence generator was updated to include N_c [10]. Thanks to Mitsuo Sakamoto (Couei Corp, Japan) for helping us out with this bug and kindly providing an updated version of the Gold Sequence generation that is also $\sim$ 40x faster.
  - Added comment on issues that may arise from using random number generators and parallel simulations.
  - Added support of user equipment feedback (CQI, RI and PMI). The feedback values are evaluated as described in [18] (added a script to allow reproduction of the figures in this paper). CQI feedback is based on ESM. MIESM and EESM are supported for SINR averaging. The feedback calculation is just tested for the ZF receiver.
  - The receiver for 4x1 and 4x2 TxD mode was modified. The performance is unchanged, but execution speed has been greatly improved.
- v.1.3r620, 2010-02-18.
  - Fixed bug in the turbo decoding process. The second decoder was initialized to the interleaved systematic bits instead of zero. Due to this there is a small performance improvement in the order of 0.2 dB. Thanks to Klaus Hueske (Technische Universität Dortmund Information Processing Lab, Germany) for helping us out with this bug.
  - Fixed errors in the way the fixed scheduler object was called that made it impossible to use it. Thanks to Tommaso Balercia (Comneon GmbH, Germany) for pointing out this bug.
  - Changed structure of the simulations parameters' loading file in order to decrease the number of configuration files.
  - Added doubly dispersive channel estimation with scalable complexity [16] and related files needed to reproduce the figures from the paper.

  - Added precoding matrix indicator feedback support as described in [17] and related files needed to reproduce the figures from the paper.
- v.1.2r553, 2009-12-25.
  - Minor bugfixes and improvements.
  - Fixed bug in the rate matching process that caused the `<NULL>` bits inserted during the sub-block interleaving process to be treated as zeros (see [9]). Due to this fix the performance of the channel coding is slightly improved. Reference and example simulations included with the simulator have been updated accordingly. Thanks to Ching Hsiang Wu (Institute for Information Industry Networks and Multimedia Institute, Taipei) for pointing out this bug.
  - Fixed bug that caused poor performance of the ZF receiver. This was due to a bad noise scaling being passed on to the demapper. After the fix the ZF and Soft Sphere Decoder (SSD) receivers have the same performance for the SISO case.
  - Since according to the MathWorks,the `seqgen` function will be removed from future versions of the Communications Tollbox software, calls to `seqgen.pn` have been substituted by calls to `commsrc.pn`. See Section XII for issues this change may cause.
  - Fixed bug that caused performance decrease for fast fading simulations at high user velocities. For the decoding of the last seven OFDM symbols, the channel of the first seven OFDM symbols was used.
  - Added support of the Winner II + channel model [19]. See Section XIII on more information on how to enable this functionality.
- v.1.1r450, 2009-08-25.
  - Minor bugfixes and improvements.
  - Added Parallel and Distributed Toolbox support (parfor).
  - Added best CQI (only for SISO and fixed schedulers.
- v.1.0r400, 2009-05-15.
  - First publicly available version of the LTE Link Level Simulator.

XI. Referencing

A version of the LTE Link Level Simulator paper is available in our publication data-base **here**.

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

```
@InProceedings{EUSIPCO2009,
  author =        {Christian Mehlf\"uhrer and Martin Wrulich and Josep Colom Ikuno and Dagmar Bosanska and Markus Rupp},
  title =         {Simulating the Long Term Evolution Physical Layer},
  booktitle =     {Proc. of the 17th European Signal Processing Conference (EUSIPCO 2009)},
  month =         aug,
  year =          2009,
  address =       {Glasgow, Scotland},
  url =           {http://publik.tuwien.ac.at/files/PubDat_175708.pdf},
}
```

```
C. Mehlfhrer, M. Wrulich, J. C. Ikuno, D. Bosanska and M. Rupp, "Simulating the Long Term Evolution Physical Layer,"
in Proc. of the 17th European Signal Processing Conference (EUSIPCO 2009), Aug. 2009, Glasgow, Scotland. [Online].
Available: http://publik.tuwien.ac.at/files/PubDat_175708.pdf
```

XII. Known issues

- The 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 2010 run-time libraries be available on the computer they are run on. The runtime files can be downloaded **here** (x86) or **here** (x64).
- In order to be able to use the parallel version of the simulator (when setting `LTE_params.simulation_type` 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 [20].
- It was pointed out that in [7], the phase ϕ is not different for each sinusoid. We are using a modified version [8].

XIII. Using the WINNER Phase II channel model reference implementation

Starting with v.1.2r553, it is possible to use channels generated with the publichly-available MATLAB implementation of the WINNER Phase II Channel Model [19]. 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 `.mat` files in the `./Winner Channel Model` folder.

XIV. Questions

For questions please check our **forum**, where you will be able to post your questions/comments/bug reports. It makes it easer for you to see what other people asked and also makes it easier for us to answer you (when we have time).

XV. Mailing List

If you want to receive information about future updates you can subscribe to our LTE simulator mailing list **here**. Note that you can change the display language to english in the selection panel to the right.

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

- Dagmar Bosanska
- Josep Colom Ikuno
- Govinda Lilley
- Michal Šimko
- Christian Mehlfürer
- Stefan Pendl
- Jörg Reitterer
- Markus Rupp
- Stefan Schwarz
- Qi Wang
- Martin Wrulich

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- CRC calculations C-code: MEXed version of the code generated by pycrc [21]. Under the MIT License.
- Turbo and convolutional encoder/decoder C-code, from the Coded Modulation Library (CML) by Iterative Solutions [20]. Licensed under the GNU lesser General Public License.

Use	c-source	MATLAB functions	License
CRC generation and checking	crc16.c crc16.h crc24a.c crc24a.h crc24b.c crc24b.h	LTE_common_crc16 LTE_common_crc24a LTE_common_crc24b	MIT License [4]
Channel coding	ConvEncode.c convolutional.h maxstar.h siso.h SisoDecode.c	LTE_tx_convolutional_encoder LTE_rx_siso_decode	GNU Lesser GPL [3]

ACKNOWLEDGMENT

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