A Lightweight and Accurate Link Abstraction Model for the System-Level Simulation of LTE networks in ns-3

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ABSTRACT
In this work we present a link abstraction model for the simulation of downlink data transmission in LTE networks. The purpose of this model is to provide an accurate link performance metric at a low computational cost by relying solely on the knowledge of the SINR and of the modulation and coding scheme. To this aim, the model combines Mutual Information-based multi-carrier compression metrics with Link-Level performance curves matching, to obtain lookup tables that express the dependency of the Block Error Rate on the SINR values and on the modulation and coding scheme being used. In addition, we propose a 3GPP-compliant Channel Quality Indicator evaluation procedure, based on the proposed Link Abstraction Model, to be used as part of the LTE Adaptive Modulation and Coding mechanisms. Finally, we discuss how these contributions have been tested, validated and integrated in the ns-3 simulator.

Categories and Subject Descriptors
C.2.1 [**Network Architecture and Design**]: Network communications, wireless communication; C.2.2 [**Computer Systems Organization**]: Computer-Communication Networks-Network Protocols; I.6.5 [**Model Development**]: Modeling methodologies; I.6.8 [**Simulation and Modeling**]: Discrete event

General Terms
Keywords
LTE; OFDM; ns-3; Link Abstraction; BLER; MIESM; AMC.

1. INTRODUCTION
Long Term Evolution (LTE) [31] is today's most advanced cellular network technology, and is expected to be massively deployed in the upcoming years. It features a completely redesigned network architecture and a high performance physical layer technology natively exploiting Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple-Input Multiple-Output (MIMO) techniques. The system architecture has been simplified with respect to 3G solutions [24], defining a few key components, abandoning traditional circuit switched networking and relying to a great extent on the flexibility offered by the IP communication paradigm. For what concerns the physical layer (PHY) design, technological innovations have been introduced in order to: 1) increase user's data rates (up to 100 and 50 Mbit/s for downlink and uplink, respectively, and even higher for LTE-Advanced), 2) increase cell-edge bit-rates, 3) support high mobility (nominally up to 350 km/h) and 4) offer higher spectral efficiencies (i.e., reduced cost per bit) as well as greater flexibility in the spectrum usage with respect to 3G technology. LTE is a very versatile system, featuring many possible configurations that allow to achieve different performance tradeoffs. In the perspective of deploying and managing future LTE networks, operators and equipment vendors are strongly interested in exploring the different configurations and solutions that can achieve the best possible performance in a variety of scenarios. Ideally, this would be carried out on the field, through the analysis of real data from actual deployments. Nevertheless, experimentation is a time consuming and expensive process where, due to economical reasons, not all scenarios can be tested. Thus, simulation is appealing to perform some pre-tuning of the selected algorithms and protocols before they are deployed. In this respect, there is a tradeoff between choosing a very accurate simulation model, which typically has a high computational complexity and only allows for the simulation of a few network elements, and a more simplified model which can scale to larger scenarios but which often has a limited accuracy.

The work that we present in this paper aims at reducing the gap between these two extremes. In detail, our aim is to provide an accurate and, at the same time, computationally lightweight Link Abstraction Model (LAM) for the LTE evolved Universal Terrestrial Radio Access Network (eUTRAN). This model shall allow the accurate prediction of transport block errors at the MAC layer taking into account channel fluctuations, multi-user interference as well as physical layer configurations (bandwidth assignment, modulation, coding, etc.). Thus, we integrate this model into a Network-Level (NL) simulator of LTE, which accounts for multiple UEs and eNodeBs, and allows the simulation of the entire LTE system (including architectural components). To this end, one might of course come up with a detailed implementation of the eUTRAN procedures [4] and especially of the LTE PHY (e.g., modeling its operations at the symbol level). However, this would lead to a very complex (and generally slow) code, which would not be suitable for

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NL simulation, where the focus is on the performance of multiple (possibly many) users. A more suitable approach, which is the one that we take here, is instead that of performing some offline pre-processing based on Link-Level (LL) simulations, so as to model the influence of channel and system parameters on the PHY performance, represented by the Transport Block error rate. This pre-encoded mapping allows to retain a good amount of the accuracy of LL simulation when modeling phenomena such as multi-user interference, OFDMA bandwidth allocation and random channel realizations while not retaining their complexity, thereby allowing for better scalability.

The key contribution of this paper is the design, integration and validation of a lightweight link abstraction model for the downlink transmission of data into the LTE-EPC Network Simulator (LENA) [11] based on ns-3 [13]. In addition, we show how this link model can be exploited to design an algorithm for reporting channel quality indicator (CQI) feedback according to the 3GPP guidelines in order to test the online selection of the Modulation and Coding Scheme (MCS) for each user, subject to given BLock Error Rate (BLER) requirements.

The rest of this paper is organized as follows: in Section 2 we discuss the related literature; Section 3 introduces the link-to-system error mapping approach explaining how our error model is obtained from offline link level performance curves. In Section 4 we describe the targeted simulation platform, ns-3, along with some fundamental aspects of LTE networks. In Section 5 we illustrate the Link Performance Model (LPM), which represents the main contribution of this paper. In Section 6 we propose an improved link adaptation technique. In Section 7 we provide some practical usage examples for our link abstraction model and show the superiority of the link adaptation technique of Section 6 with respect to current approaches. In Section 8 we conclude the paper and discuss future research directions.

2. RELATED WORK

The problem of evaluating the error distribution in Orthogonal Frequency Division Multiplexing (OFDM) radio transmission techniques became popular a few years ago with the introduction of the corresponding multi-access technology, OFDMA. First of all, OFDM transmissions are affected by complex propagation phenomena due to the time-frequency selective channel nature. This implies that subcarriers may experience frequency selective fading and are therefore affected by different channel gains. On top of this, OFDMA further increases the system complexity as subcarriers are assigned to different users, whose signals are usually generated with different transmission powers and MCSs. This makes the task of predicting the error distribution per user rather complex, in terms of both collecting a reduced subset of parameters to describe performance trends, and generating a flexible error model in order to cover all possible scenarios. With respect to this, most of the previous developments adopted Link-to-System Mapping (LSM) as a lightweight, general and flexible framework [20, 28, 33].

The firsts steps towards the practical application of this solution have been taken during the evaluation of the Worldwide Interoperability for Microwave Access (WiMAX) radio technology by the IEEE 802.16 task force. WiMAX was the first system to adopt OFDMA, thus several LSM techniques have been applied and evaluated [34] for it prior to LTE oriented research. On this matter, two extensions of the well known network simulator 2 (ns-2) [12] called WINSE [15] and WiDe [26] had these solutions integrated; however, their code is not publicly available.

Moving to LTE systems, the problem has been extensively investigated in the last few years. Many papers have exploited LSM techniques in order to propose and evaluate interference management and allocation schemes [16, 25]. However, only a few of them made the simulation tool [22, 23] publicly available. [22] refers to a set of Matlab simulators, both LL and SL, that aim at providing a comprehensive framework for the simulation of link and MAC layer performance. The design choices of Matlab and the focus on lower layer aspects do not give to this tool the possibility of evaluating complex network scenarios, featuring mobility and traffic constraints. Some of these assumptions have been relaxed in [23], where c++ was adopted as the programming language and some networking functionalities were included. However, these simulators are designed to mostly evaluate lower layer statistics and do not account for the core LTE system, the so called Evolved Packet Core (EPC), in charge of handling, among other aspects, bearers, their Quality of Service (QoS), mobility, and Radio Resource Management (RRM).

Recently, a new module, called LENA, has been developed for LTE as an extension of the ns-3 simulator. LENA already includes EPC functionalities [19] and is designed in a product oriented fashion (i.e., it implements the Scheduling APIs defined by the Small Cell Forum [32], formerly known as Femto Forum). It is to be noted that LENA has all the advantages of a large open source project, i.e., the support of a lively community for what concerns debugging, validation and maintenance.

3. LINK-TO-SYSTEM ERROR MAPPING

Our main objective in this paper is to increase System Level (SL) simulation reliability by introducing an efficient error model based on link level results, while maintaining a reasonably small computational cost. First, we recall the distinction between SL and LL simulators. A system-level simulator enables a network-based analysis, mostly concerning RRM issues, such as resource allocation, mobility and interference management, whereas a link-level simulator focuses on point-to-point communication, evaluating the impact of physical layer aspects such as channel coding-decoding, MIMO gains and so forth.

For an accurate evaluation of the user's performance, besides the MCS assigned by the LTE scheduler, it is important to track the residual errors, i.e., after link layer processing, that are due to channel phenomena such as fading, multiple-access interference, etc. However, as discussed above, a comprehensive simulation of link layer procedures would entail a high computational complexity, which is undesirable for multi-user scenarios. With these objectives in mind, we propose here a lightweight approach to map physical layer parameters such as SINR and MCS onto higher layer BLock Error Rate values. With BLER we refer to the residual error rate after all PHY-layer procedures, i.e., affecting the code blocks at the output of the turbo decoder at the receiver side. The procedure that we adopt is illustrated in Fig. 1: the system level engine of the LTE simulator (SL in the figure) returns SINR values for each resource block (from 1 to N) for all users. Thus, for each user we pick the instantaneous SINR vector $(SINR_1, SINR_2, \ldots, SINR_N)$and map it onto a Mean Mutual Information per coded Bit (MMIB) metric according to the MIESM method, e.g., see [21]. The obtained MMIB is a time-varying compressed representation of the channel quality as perceived by any given user at any given time.

In addition, we store offline calculated curves returning the BLER as a function of the SINR (considering an AWGN channel model) for each valid (MCS, $\mathrm{CB}_{\mathrm{size}}$) pair, where MCS is a modulation and coding scheme and CB_{size} represents the code block size. These curves have been obtained with the Vienna link level simulator [14, 27] (LL in the figure).

Finally, this offline calculated SINR to BLER mapping is utilized, together with the instantaneous MMIB information, to obtain the BLER traces for each user. This procedure is explained in greater detail in the following Section 5.

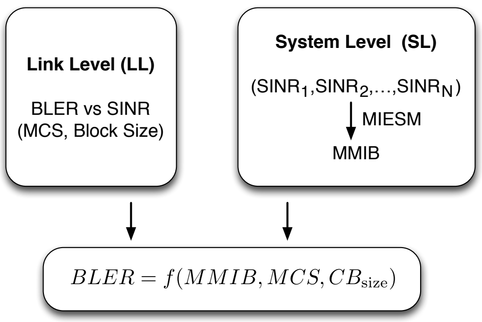

Figure 1: High level description of the link-to-system error mapping

4. SIMULATOR OVERVIEW

The simulation platform used to test and validate our contributions is ns-3, an open source discrete-event network simulator for Internet-based systems, available online at [13]. Our work extends the LTE module currently under development within the project LENA [11], which comprises the LTE core network, EPC, presented in [19], and the radio access, eUTRAN, detailed in [18] and based on the first LTE simulation framework for ns-3 [29]. The simulator is extensively documented in [10].

In Fig. 2 we show a flow diagram that represents the LTE transmission procedure in ns-3. Basically, the signal quality (CQI in the figure) at any given receiver is tracked for each of the subchannels allotted to it. Based on this information, a scheduler assigns a suitable MCS, which characterizes the bit rate at which the data is transferred over the channel for that particular user. However, the current ns-3 LTE implementation lacks an error prediction model, which means that once a transmission opportunity is scheduled, the corresponding data is always correctly received at the bit rate permitted by the chosen MCS. Our goal is to improve upon this link layer model by allowing for a more accurate evaluation of the physical downlink shared channel (PDSCH), taking into account decoding capabilities and residual errors after link layer processing at the receiver.

In the following, we provide a brief description of the key features of the ns-3 module for LTE networks.

Spectrum Model: the spectrum framework adopted in ns-3 was presented in [17]. The frequency model designed by Baldo et al. represented a fundamental building block for the realization of the LTE radio spectrum, which is specified in [2]. The frequency axis is subdivided in sub-bands with a carrier frequency raster of 100 kHz, whereas B is the transmission bandwidth configuration expressed in number of Resource Blocks (RB), as shown in Table 1.

The LTE frame is composed of 10 subframes of 1 millisecond each, for a total duration of 10 milliseconds. As shown in Fig. 3, each subframe can be seen as a *time* vs *frequency* grid. Resources in LTE can be allotted to the users in terms of an integer number of Resource Blocks (RB), where the RB is the allocation quantum. Each RB is 180 kHz wide in frequency (12 subcarriers, 15 kHz each) and 14 OFDM symbols in time (1 ms).

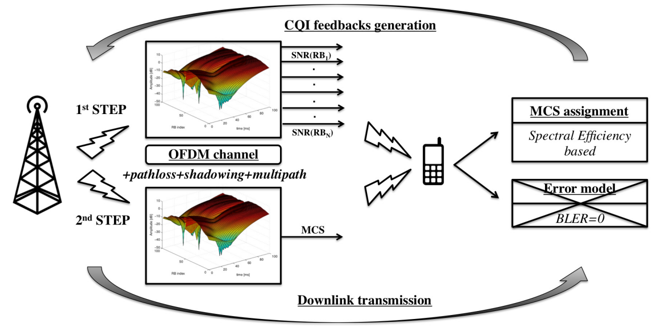

Figure 2: ns-3 transmission diagram

Bandwidth *B* (MHz)	Number of RBs
1.4	6
3	15
5	25
10	50
15	75
20	100

Table 1: Maximum number of RBs that can be assigned to a given LTE UE as a function of the selected channel bandwidth

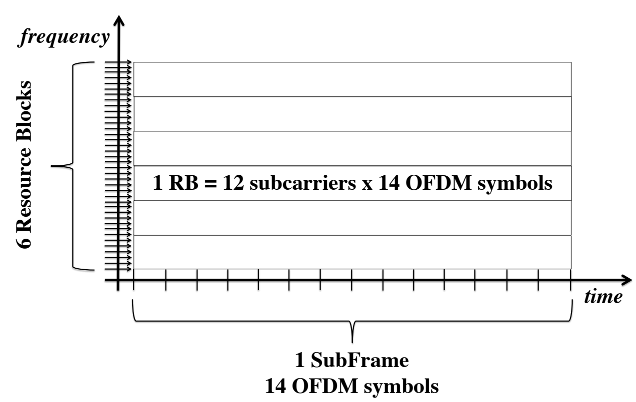

Figure 3: LTE subframe structure (B = 1.4 MHz)

Channel Model: all the channel modules developed for the ns-3 simulator can be used for LTE. Thus, any ns-3 compliant path loss and/or shadowing model can be plugged in. For what concerns fading phenomena, the propagation conditions defined in Annex B.2 of [3] have been used to generate channel traces for three different scenarios, as shown in Table 2.

Interference Model: the PHY model is based on the well-known Gaussian interference channel, according to which interfering signals' powers, in linear units, are summed up to determine the overall interference power. The resulting Signal to Interference plus

Scenario	UE speed (kmph)
Pedestrian	0, 3
Vehicular	30, 60
Urban	0, 3, 30, 60

Table 2: 3GPP propagation scenarios

Noise Ratio (SINR) expression for a given RB is given by

$$SINR = \frac{|h_0|^2 P_{t,0}}{\sum_{i=1}^{N_I} |h_i|^2 P_{t,i} + \sigma_0^2}, \tag{1}$$

where $P_{t,0}$ and h_0 are the transmission power and the channel gain for the useful transmission respectively, N_I is the number of interferers, whereas $|h_i|^2$ and $P_{t,i}$ represent the channel gain and the transmission power of the i-th interferer. σ_0^2 is the power of the thermal noise.

CQI feedbacks: prior to transmission, each eNodeB broadcasts a signaling pilot sequence. All the UEs within its coverage area decode it, and generate a list of Channel Quality Indicators (CQI) on a per sub-channel basis, in order to provide the eNodeB with an overall quality information snapshot. CQI feedbacks [4] represent an indication of the data rate that can be supported by the channel for allocation and scheduling purposes, as shown in Table 3. In LENA, the generation of CQI feedbacks is done according to the primitives specified in [32].

MCS no.	Modulation	Spectral Efficiency	Effective Coding Rate (ECR)
1	QPSK	0.15	0.08
2	QPSK	0.19	0.1
3	QPSK	0.23	0.11
4	QPSK	0.31	0.15
5	QPSK	0.38	0.19
6	QPSK	0.49	0.24
7	QPSK	0.6	0.3
8	QPSK	0.74	0.37
9	QPSK	0.88	0.44
10	QPSK	1.03	0.51
11	16QAM	1.18	0.3
12	16QAM	1.33	0.33
13	16QAM	1.48	0.37
14	16QAM	1.7	0.42
15	16QAM	1.91	0.48
16	16QAM	2.16	0.54
17	16QAM	2.41	0.6
18	64QAM	2.57	0.43
19	64QAM	2.73	0.45
20	64QAM	3.03	0.5
21	64QAM	3.32	0.55
22	64QAM	3.61	0.6
23	64QAM	3.9	0.65
24	64QAM	4.21	0.7
25	64QAM	4.52	0.75
26	64QAM	4.82	0.8
27	64QAM	5.12	0.85
28	64QAM	5.33	0.89
29	64QAM	5.55	0.92

Table 3: LTE Modulation and Coding Schemes (MCS)

Scheduling & Resource Allocation: the scheduler is in charge of generating specific structures called Data Control Indication (DCI), which are then transmitted by the eNodeB through the Physical Downlink Control Channel (PDCCH) to the connected UEs, in order to provide them with a resource allocation map in every subframe. These control messages contain information such as the MCS to be used, the MAC Transport Block (TB) size, and the allocation bitmap which identifies the RBs that will carry the data transmitted by the eNodeB to each user.

5. LINK PERFORMANCE MODEL

As we discussed above, we aim at introducing a prediction error model for downlink data transmission in LTE. In Fig. 4 we show our contribution to the ns-3 LTE implementation, which is twofold: on the one hand, we account for a lightweight error model so as to track the residual errors after link layer processing at the receiver, on the other hand, we propose an improved MCS assignment scheme supported by a new CQI evaluation scheme based on 3GPP guidelines. Note that this novel algorithm for CQI evaluation could not be tested in the previous simulator as it is based on residual error estimates.

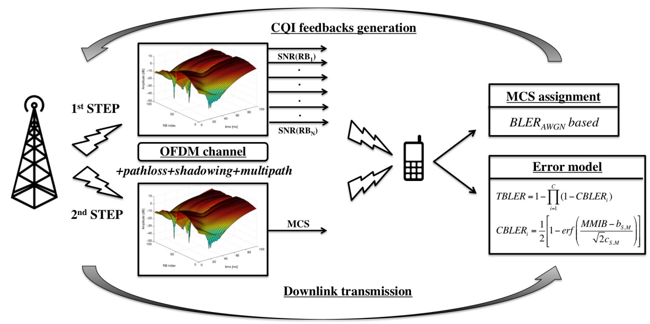

Figure 4: Improved ns-3 transmission diagram

The link level simulations executed to build our abstraction model assume a frequency flat channel response at any given SINR (the so-called AWGN channel). In order to illustrate the general procedure that we adopted to map SINR levels onto error curves, in the following paragraph we disregard the RB concept and refer to LTE OFDM sub-channels. The procedure will be specialized to RBs in Section 5.1.

Given that, let us assume that the simulator returns an instantaneous SINR sample for each LTE sub-channel, which means a vector $(SINR_1, SINR_2, \ldots, SINR_{N_{\rm sub}})$, where $N_{\rm sub}$ is the number of LTE sub-channels. In order to obtain a lightweight and effective mapping from this vector to a single BLER metric we consider the *effective SINR mapping* (ESM) method, see [7]. Briefly, the instantaneous SINR vector is mapped onto a single scalar value as follows [28]:

$$eSINR = \alpha_1 I^{-1}\left(\frac{1}{N_{\rm sub}}\sum_{i=1}^{N_{\rm sub}} I\left(\frac{SINR_i}{\alpha_2}\right)\right), \tag{2}$$

where $I(\cdot)$ represents the *information measure* function, $I^{-1}(\cdot)$ is its inverse, whereas α_1 and α_2 are two scaling parameters that are tuned as a function of the selected MCS (more about these parameters will be said shortly). As shown in Table 4, several information measure functions have been tested in the literature.

The results provided in [21] demonstrate that the MIESM method outperforms all the other mapping approaches in terms of approx-

Effective SINR Mapping	Information Measure
Capacity (CESM) [9]	$I(x) = \log_2(1+x)$
Logarithmic (LESM) [8]	$I(x) = \log_{10}(x)$
Exponential (EESM) [5]	$I(x) = e^{-x}$
Mutual Information (MIESM) [6]	$I(x) = MI(x)$

Table 4: Information measure functions tested in the literature

imation accuracy for the BLER curves. Thus, we adopted the Mutual Information (MI) metric for our implementation.

5.1 MIB Mapping

As reported in [7], the Mutual Information per coded Bit (MIB) can be approximated through the following function:

$$J(t) \simeq \begin{cases} a_1 t^3 + b_1 t^2 + c_1 t, & t < 1.6363 \\ 1 - e^{(a_2 t^3 + b_2 t^2 + c_2 t + d_2)}, & 1.6363 \leq t \leq \infty \end{cases}, \quad (3)$$

where the parameters have been obtained through numerical fitting and are reported in the following Table 5.

$0.001 \leq t < 1.6363$	$1.6363 \leq t \leq 1000$
$a_1 = -0.04210661$	$a_2 = 0.00181492$
$b_1 = 0.209252$	$b_2 = -0.142675$
$c_1 = -0.00640081$	$c_2 = -0.0822054$
–	$d_2 = 0.0549608$

Table 5: J-function approximation parameters

Specifically, it has been demonstrated [7] that the MIB of any modulation m can be approximated as a mixture of $J(\cdot)$ functions as follows:

$$I_m(x) = \begin{cases} 0, & x < 0.001 \\ \sum_{k=1}^{K} \alpha_k J(\beta_k \sqrt{x}), & 0.001 \leq x \leq 1000 \\ 1, & x > 1000 \end{cases}, \quad (4)$$

where $\sum_{k=1}^{K} \alpha_k = 1$ for some $K \geq 1$ and the argument x is the SINR associated with the transmission channel under study. We note that for $x < 0.001$, i.e., SINR smaller than -30 dB, the mutual information is fixed to 0, whereas for $x > 1000$, that is SINR bigger than 30 dB, the mutual information is assumed to be always equal to 1. Numerical fittings have been carried out (see again [7]) to obtain K, α_k and β_k for QPSK, 16-QAM and 64-QAM, as reported in the following Table 6.

Modulation m	MIB function $I_m(x)$, $0.001 \leq x \leq 1000$
QPSK	$J(2\sqrt{x})$ (exact)
16-QAM	$\frac{1}{2}J(0.8\sqrt{x}) + \frac{1}{4}J(2.17\sqrt{x}) + \frac{1}{4}J(0.965\sqrt{x})$
64-QAM	$\frac{1}{3}J(1.47\sqrt{x}) + \frac{1}{3}J(0.529\sqrt{x}) + \frac{1}{3}J(0.366\sqrt{x})$

Table 6: Numerical approximations for MIB mapping

Next, we specialize Eq. (2) to the case of practical interest where SINR values are acquired for each resource block. Let $SINR_n$ be the instantaneous SINR value associated with a given RB n, where $n = 1, 2, \ldots, N$ and N is the number of RBs allotted to the user. According to the above discussion, the function $I_m(x)$ can be used to map $SINR_n$ onto the corresponding mutual information domain, where m is the adopted modulation scheme. Note that the argument x corresponds to $SINR_n$ and in LTE, for each subframe, the same modulation is picked for all RBs. Given all that, the

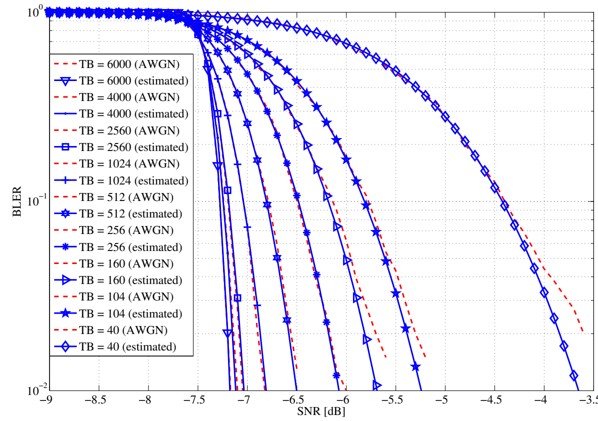

Figure 5: BLER for MCS 1

Mean Mutual Information per coded Bit (MMIB) can be obtained as follows:

$$MMIB = \frac{1}{N} \sum_{n=1}^{N} I_m(SINR_n), \quad (5)$$

where N is the number of RBs assigned to a specific user and m is the modulation that this user is exploiting. To sum up, the model starts by evaluating the mutual information value for each RB from the corresponding SINR samples. Subsequently, the MMIB is computed by averaging (effective SINR mapping) the corresponding mutual information values as per Eq. (5).

5.2 BLER prediction

The data at the MAC layer of the LTE protocol stack (right above the LTE PHY) is arranged in Transport Blocks (TB), whose size depends on the specific configuration of the underlying PHY. TBs are split into a number of CBs which are independently encoded by the turbo encoder at the PHY layer. Each CB is then encoded and transmitted over the channel exploiting the N RBs allotted to the user, see Section 4. In this section we show how to efficiently compute the Transport BLock Error Rate (TBLER) from the results of Section 5.1.

For the moment, let us focus on the i-th CB of a given TB. As mentioned in Section 3, link-level simulations (whose results were obtained using the Vienna LL simulator) have been used to obtain the PHY-layer performance in terms of BLER vs SINR over AWGN channels, accounting for the configuration of the PHY-layer turbo encoder in terms of Code Block (CB) length and selected MCS. The 3GPP standard has been considered to assess the correct CB sizes in the simulations, according to [4]. As an example, the dotted lines in Figs. 5 and 6 show the BLER as a function of SINR for MCS 1 and 29, respectively. These curves have been calculated offline considering the actual LTE PHY layer procedures. As can be seen from these plots, the CB size highly impacts the actual BLER performance for a given MCS.

As mentioned above, the selected CB i is transmitted over the channel using the N RBs that are assigned to the user. At the receiver side, a reference SINR value[1] is made available by our ns-3 system level simulator for each of these RBs, returning the SINR vec-

[1] We assume no frequency selectivity among the 12 sub-carriers composing the resource block.

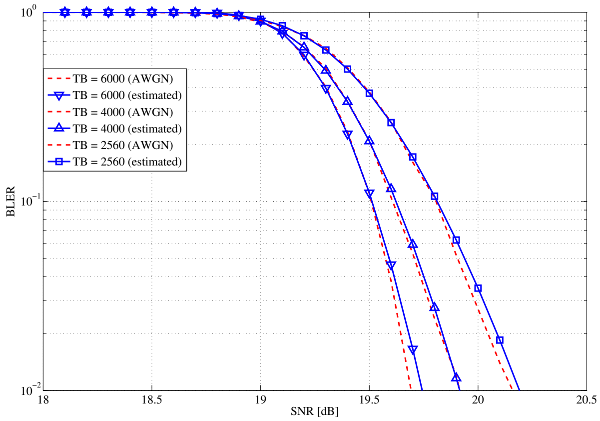

Figure 6: BLER for MCS 29

tor $(SINR_1, SINR_2, \ldots, SINR_N)$, as discussed in Section 3. From here, we obtain the MMIB metric using Eq. (5), as explained in Section 5.1. This MMIB corresponds to an equivalent SINR for the transmission of CB i over the allotted RBs. As a last step to obtain the residual error rate of CB i, we need to map its MMIB onto the corresponding BLER, which is referred to here as $CBLER_i$. This is done according to the following procedure.

In order to reduce the computational burden at simulation time as much as possible, an approximation based on the Gaussian cumulative model has been adopted. According to this, the estimated BLER curves as a function of MMIB are parameterized as follows:

$$CBLER_i(x) = \frac{1}{2}\left[1 - \text{erf}\left(\frac{x - b_{S,M}}{\sqrt{2}c_{S,M}}\right)\right], \tag{6}$$

where x is the MMIB associated with CB i, $b_{S,M}$ represents the so called "transition center" and $c_{S,M}$ is the "transition width" of the Gaussian cumulative distribution. S is the code block size and M is the MCS, which dictates the actual transmission rate, as shown in Table 3. What we did at this point, was to find suitable pairs $(b_{S,M}, c_{S,M})$ for each MCS and code size. We did so through numerical fitting so that the curves from Eq. (6) would match those obtained from the Vienna LL simulator. The result of this procedure is shown in Figs. 5 and 6, where the solid curves represent the result of Eq. (6) where we have used the best fitting $(b_{S,M}, c_{S,M})$ pair for each MCS and code size. As can be seen from these plots, the approximated BLER from Eq. (6) (solid lines) closely match the BLER obtained through the numerical simulation of LTE PHY procedures (dotted lines).

To sum up, for any given code block i, the corresponding $CBLER_i$ is computed as follows:

1. Obtain the SINR vector $(SINR_1, SINR_2, \ldots, SINR_N)$ for CB i.
2. Obtain the MMIB from this SINR vector using Eq. (5).
3. Use the selected CB size S and MCS M to pick the best fitting parameters $(b_{S,M}, c_{S,M})$ from a lookup table, computed offline.
4. Use this pair $(b_{S,M}, c_{S,M})$ with Eq. (6) to obtain $CBLER_i$.

The overall Transport BLock Error Rate (TBLER) is thus found as:

$$TBLER = 1 - \prod_{i=1}^{C}(1 - CBLER_i), \tag{7}$$

where C is the number of CBs contained in the TB.

Lookup tables: to limit the computational complexity and the memory space taken by the proposed link abstraction model, we only considered a subset of CB sizes, i.e., $\mathcal{S} = \{40, 104, 160, 256, 512, 1024, 2560, 4000, 6000\}$ bits. This choice is aligned with the typical performance of turbo codes, where large CB sizes do not strongly affect BLER performance. However, we note that for CB sizes smaller than 1000 bits, the BLER performance might significantly differ as we vary the block size (up to nearly 3 dB). Therefore, we accounted for an unbalanced quantization of CB sizes in order to get more accuracy in the critical zone (small code blocks). This is particularly evident from Fig. 5 that shows a similar BLER profile for large CB sizes (e.g., 2500, 4000 and 6000 bits), whereas the performance gap increases as the CB size gets smaller. Thus, $(b_{S,M}, c_{S,M})$ parameters have been tabulated for all valid combinations of MCS and block sizes in set $\mathcal{S}$. We remark that high MCS values with high order modulations and efficient coding rate schemes, such as 64-QAM with an Effective Coding Rate (ECR) of 0.92 (i.e., MCS 29), see Fig. 6, allow for a minimum CB size of 2560 bits. The latter is much larger than the minimum size at small MCS values, e.g., MCS 1, where the minimum size is 40 bits, see Fig. 5. This reflects the fact that turbo coding offers better performance as the code block size increases; thus, for high order modulations such as MCS 29, small code block lengths are inefficient as the resulting BLER performance is unacceptable.

6. LINK ADAPTATION IMPROVEMENT

Link adaptation plays a fundamental role in modern wireless communications systems, which need to face issues such as strong interference from multiple users and their mobility, which makes the wireless channel frequency selective. These facts are coped with by LTE adaptive modulation and coding algorithms. Focusing on the downlink scenario, AMC has the role of tracking the perceived SINR and sending back to the base station (eNodeB) a so called CQI report. Hence, periodically, the UE reports to the eNodeB a single CQI value for all the RBs (the so called *wideband* CQI). This information is a "compressed" representation of the quality experienced by the UE in a specific sub-frame and is used at the base station side for the selection of the MCS. This process is continuously executed so as to adapt to channel and network dynamics.

In this section, we propose a SINR to CQI mapping approach based on the link error abstraction model presented above. As a competing approach we consider the algorithm that is currently implemented in the LENA ns-3 simulator, which is inspired by the *spectral efficiency* concept, see also [30].

Spectral efficiency-based approach: consider the generic RB i, and let $SINR_i$ be the corresponding SINR value, in linear units. We obtain the spectral efficiency η_i of RB i using the following equations:

$$\Gamma = -\frac{\ln(5\,\text{BER})}{1.5}, \tag{8}$$

$$\eta_i = \log_2\left(1 + \frac{SINR_i}{\Gamma}\right), \tag{9}$$

where BER is the Bit Error Rate and Γ is the so called *SNR gap*, as it models the discrepancy between practical implementations and information-theoretic results.

Upon the calculation of η_i, which lies in the continuous interval $[0.15, 5.55]$ (see Table 3), the procedure described in [1] is used to derive the corresponding CQI, which is a quantized version of η_i.

Algorithm 1 CQI assignment performed by each UE. Prior to this computation, the users decode the pilot sequence sent by the eNodeB in order to get all the RB SINR samples that are needed to retrieve the predicted error rate.

Require: Target TBLER ($TBLER_{\text{th}}$), $\overline{SINR}_{UE}$
  for $i = 1 \to N_{UE}$ **do**
    $MCS \leftarrow 29$
    while $MCS > 0$ **do**
      $TBLER_i \leftarrow GetTbError(\overline{SINR}_i, MCS)$
      if $TBLER_i < TBLER_{\text{th}}$ **then**
        $break$
      else
        $MCS - -$
      end if
    end while
    $CQI_i \leftarrow GetCorrespondingCqi(MCS)$
  end for

Error model-based approach: this model relies on the exploitation of our link abstraction model. Thanks to this approach, we can dynamically select the MCS that better complies with a given target transport block error rate for the connection, referred to as $TBLER_{\text{th}}$. In the following, we describe our improved CQI evaluation procedure by abstracting away from the actual implementation details, i.e., on the actual representation of CQI values (at the receiver, e.g., number of CQI levels, etc.) and the subsequent mapping of these CQIs onto a suitable MCS (which is done at the eNodeB).

Our procedure, which is reported in Algorithm 1, works as follows. Periodically, each UE computes its received power spectrum profile, i.e., a SINR sample is acquired for each possible RB.[2] For any given user $i = 1, 2, \ldots, N_{UE}$, it starts from MCS 29, which corresponds to the most aggressive transmission scheme and evaluates the TBLER performance considering a transport block composed of all possible LTE RBs. The transport block error rate for user i, $TBLER_i$, is estimated through Eq. (6), taking as input the vector of SINRs for the selected user, $\overline{SINR}_i$, and the MCS that we are currently evaluating. If $TBLER_i$ is larger than or equal to the target BLER defined by 3GPP (i.e., 0.1) [4], we keep on searching for a better (less aggressive) MCS, the procedure stops otherwise. Thus, the corresponding CQI is obtained in order to satisfy the spectral efficiency constraints defined by the standard [4] and reported in Table 7.

From eNodeB's perspective, the CQI mapping to MCS can be returned by inverting the mapping of Table 7.

7. SIMULATION RESULTS

In the following we provide some technical results for selected LTE scenarios. Our main goals are: 1) to illustrate the usability of the proposed link abstraction model, and 2) to prove the efficiency of the link adaptation improvement proposed in Section 6. In Table 8 we report the considered system parameters.

[2] In this case, all RBs allowed by the selected LTE channel bandwidth are accounted for, according to Table 1.

CQI Index no.	Modulation	Spectral Efficiency
0	out of range	-
1	QPSK	0.1523
2	QPSK	0.2344
3	QPSK	0.3770
4	QPSK	0.6016
5	QPSK	0.8770
6	QPSK	1.1758
7	16QAM	1.4766
8	16QAM	1.9141
9	16QAM	2.4063
10	64QAM	2.7305
11	64QAM	3.3223
12	64QAM	3.9023
13	64QAM	4.5234
14	64QAM	5.1152
15	64QAM	5.5547

Table 7: CQI coding table

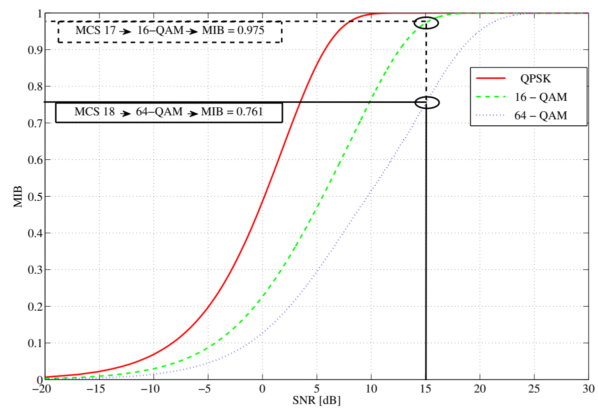

Figure 7: Example 1 - MI extraction

1) Error model: we consider a downlink transmission from an eNodeB to a single static UE. For the wireless channel, we account for a Friis free-space propagation model, but note that the conclusions that we draw here are general and apply to more sophisticated models as well. The UE is placed 2150 meters away from the eNodeB and, according to the considered propagation loss model, it experiences a SNR of 15.1 dB for all its RBs.

We first evaluate the BLER performance resulting from the selection of a "safe" transmission scheme, MCS 17, which corresponds to 16QAM (4 bits per OFDM symbol). As we now show, for this MCS the estimated error rate (through Eq. (6)) is below the standard TBLER threshold of $TBLER_{\text{th}} = 0.1$. First of all, we extract the *mutual information* value associated with the experienced SNR, as shown in Fig. 7 (where we plot the approximation functions of Table 6). According to [4], from the selected MCS and the maximum number of assignable RBs (see Table 1) the TB size is 7272 bits (including the header). Following [4], the TB is split into two code blocks, CB_1 and CB_2, of size 3684 and 3584 bits, respectively. As shown in Fig. 8, these code sizes are mapped onto the closest CB size in set $\mathcal{S}$. In fact, as per our discussion in Section 5.2, in our ns-3 simulator fitting parameters are only stored

PHY Configuration	
Parameter	**Value**
Frequency	2.1 GHz
Channel Bandwidth	5 MHz
Propagation Model	Friis free-space
Number of RBs	25
$RB_{bandwidth}$	180 kHz
$RB_{subcarriers}$	12
$RB_{OFDMsymbols}$	14
eNodeB TX power	30 dBm
Noise figure (F)	5
Noise spectral density (N_0)	-174 dBm/Hz

Table 8: Main system parameters

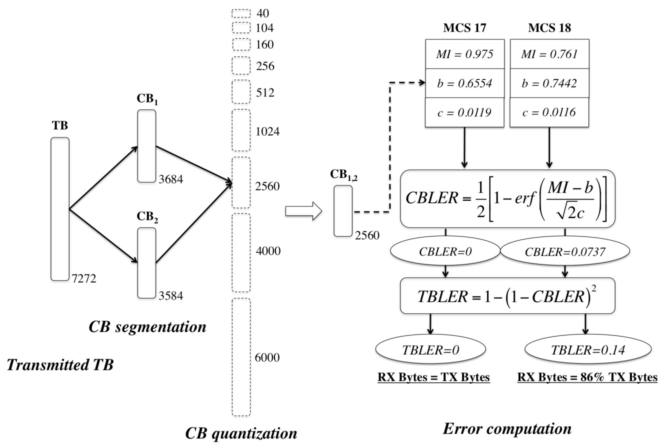

Figure 8: Example 1 - TBLER computation

for a subset of all possible CB sizes. Thus, the resulting CB size that will be used for the prediction of the CBLER performance is 2560 bits. Now, using the $b_{S,M}$ and $c_{S,M}$ parameters associated with the latter code block size and the previously extracted MI with Eqs. (6) and (7), we obtain an estimated transport block error rate of $TBLER = 0$.

Next, we try to allocate a more aggressive modulation and coding scheme, MCS 18, for which the modulation order amounts to 6 bits per OFDM symbol (64QAM). Thus, we repeat the procedure illustrated in the previous paragraph, obtaining the mutual information MI, and the fitting parameters $b_{S,M}$ and $c_{S,M}$. These quantities, together with Eqs. (6) and (7) return $TBLER = 0.14$, which mean that MCS 18 is not compatible with the considered error requirements.

2) Link adaptation: we now consider a scenario with a single UE, where we vary its distance from the eNodeB. This leads to SNR values ranging from about 2 to 30 dB. Also, we consider the standard target transport block error rate of $TBLER = 0.1$. In Fig. 9, we show the effective spectral efficiency as a function of the SNR for the spectral efficiency-based (SE_MCS) and the error-based (EM_MCS) MCS selection schemes. The effective spectral efficient metric reflects the actual bits per second per unit of frequency that are successfully transmitted from the eNodeB to the UE, by also accounting for the residual error after PHY-layer processing. As can be seen from Fig. 9, EM_MCS outperforms the current approach, at all SNR levels. This indicates that SE_MCS

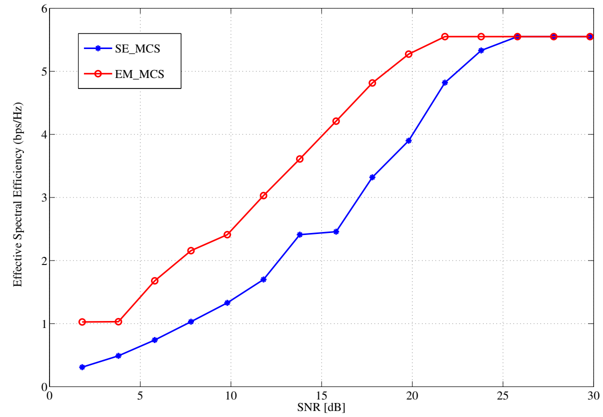

Figure 9: MCS assignment comparison

tends to be too conservative, even though a more aggressive technique can be used while still adhering to the target error requirements.

8. CONCLUSIONS & FUTURE WORK

In this work we introduced a link abstraction model for the system-level simulation of downlink traffic in LTE networks using ns-3. Our objective here has been to provide a lightweight but still accurate procedure for the computation of the residual errors, after PHY-layer processing, without having to go through the detailed simulation of LTE PHY procedures. Toward this end, we combined Mutual Information-based multi-carrier compression metrics with Link-Level performance curves matching. This allowed us to obtain pre-calculated lookup tables, which can be used in an online fashion to track residual bit errors after physical layer modulation and coding procedures. In addition, we have proposed a Channel Quality Indicator evaluation procedure which can be used as part of the LTE Adaptive Modulation and Coding scheme, showing its superiority in terms of achievable spectral efficiency with respect to current ns-3 solutions. As future work we plan to investigate algorithms for resource allocation, especially targeting the transmission of streaming flows over LTE networks.

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