On Scalability, Robustness and Accuracy of physical layer abstraction for large-scale system-level evaluations of LTE networks

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***Abstract*—We present an in-depth performance analysis of the gains of physical layer (PHY) abstraction when compared to a full implementation of the physical layer. The abstraction model uses either effective signal to noise plus interference (SINR) mapping or mutual information effective SINR mapping and covers different transmission modes as well as support for hybrid automatic repeat request. Using the OpenAirInterface LTE system level simulator we show that for a simple network with one base station and two user equipments these PHY abstraction techniques decrease the simulation time by a factor of up to 100 while providing the same accuracy as with the full PHY implementation.**

Parameter	Value
No. eNBs	1
No. UEs	1
Path loss model	$\mathrm{PL}_{\mathrm{dB}} = 128 + 36.7 \cdot \log_{10}(d_{\mathrm{km}})$
UE distribution	fixed at distance of $d = 0.32$km from eNB
TX power	15dBm
RX noise figure	0dBm
Antenna gains	0dBm
Resulting SNR	10dB
Large scale fading	none
Small scale fading	SCM-C
System bandwidth	5MHz (25 ressource blocks)
TDD configuration	3 (6 DL, 3 UL, 1 special subframe)
Cyclic Prefix	normal
Transmission Mode	1 (SISO)
Antennas at eNB/UE	1/1
Link adaptation	fixed MCS 7
Resulting max throughput	1.867 Mbps
Trafic model	full buffer

TABLE I. SIMULATION PARAMETERS

I. INTRODUCTION

System level simulations are an integral part of performance evaluations of mobile communication networks. Typically these system level simulators implement small networks with 10-20 base stations (called eNB in LTE) and several hundred user equipments (UEs). Also channel models, mobility models, and traffic models are often also included in such simulators. To motivate the use of physical layer (PHY) abstraction in system level simulators consider the following example experiment, carried out using the OpenAirInterface LTE system level simulator (oaisim) [1]. The top-level parameters of the experiment are given in Table I. Note that the OpenAirInterface uses heavily optimized C code and single-input multiple-data (SIMD) instructions, both for the MODEM and for the channel convolution. The experiment has been carried out on a PC with an Intel Core i5 CPU running at 3.33GHz. The process has been pinned to one CPU and its priority has been set to the maximum to avoid swapping. An overview of where time is spent in the system level simulator is given in Figure 1, which shows the processing time needed for one subframe (1ms). It can be seen that 85% of the time is spent in the channel simulation, that is generation of the random channel, interpolation to the right sampling rate, and convolution of the signals with the channel. Although the UE's receiver is operating at its full capacity, it only makes up 10% of the total simulation time. In total 95 % of the simulation time is spent on the PHY and the channel.

II. OVERVIEW OF PHYSICAL LAYER ABSTRACTION TECHNIQUES

A. Introduction

PHY abstraction is the process of modeling the performance of the physical layer (in terms of block error rates or throughput) as a function of the radio channel without running the time consuming MODEM and the channel convolution. The model takes into account the power and resource allocation, the modulation and coding scheme (MCS) and the current channel state, i.e., path loss, shadowing, fading and interference. In case multiple antennas are used at the transmitter and/or receiver (creating a multiple-input multiple-output (MIMO) channel), also the precoding and the receive processing is taken into account. PHY abstraction models are useful for two different purposes: Firstly they can be used in the implementation of a UE to compute the feedback (channel quality information - CQI) and secondly they can be used in large-scale system level simulations to speed up simulation time.

The two most important PHY abstraction methods are Exponential effective SINR mapping (EESM) and Mutual Information based SINR mapping (MIESM). EESM was first introduced in [2] for system level evaluations and since then it has been extensively used for link quality modeling. In [3] it is shown that EESM is a suitable choice for 3GPP LTE wireless systems and it outperforms the other schemes. Further it was

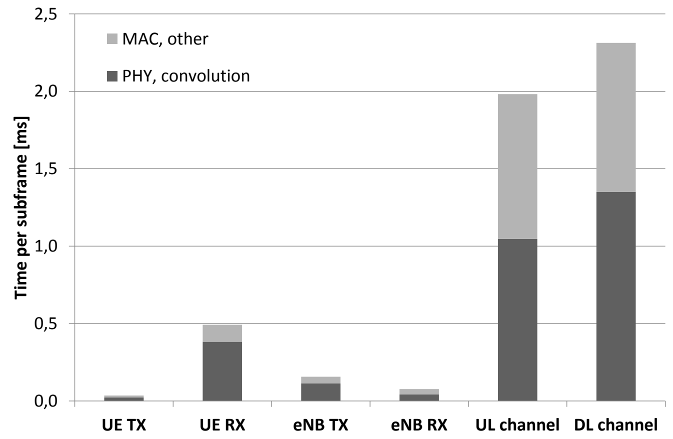

Fig. 1. Computation time spent in the different elements of a system level simulator.

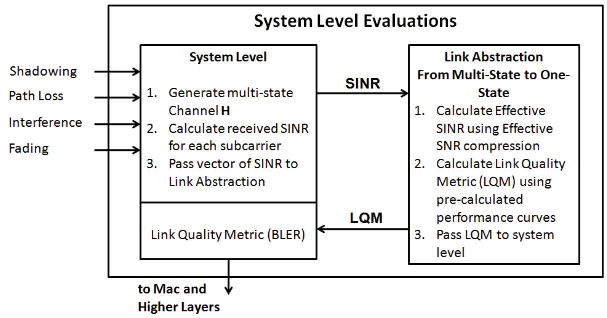

Fig. 2. PHY abstraction model

demonstrated that training of link abstraction is independent of the used channel model.

While EESM is very attractive because of its simplicity, MIESM is much better suited to model more advanced (non-linear) receiver architectures, hybrid automated repeat request (HARQ), and MIMO transmission modes [4]. In [5] the authors have used the observation that decoding of a codeword is independent of modulation so they have devised a two step method where received bit information rate is used as a link quality measure instead of effective SINR. This method is also mutual information based and does not require the calibration for convolution and turbo decoders and was selected as an evaluation methodology in the WINNER project [6] and the WiMAX standard [7]. MIESM is also very well suited to model HARQ as shown in [8–10].

An important work in the field of MIMO communications was presented in [11] where the authors have presented a semi-analytical performance prediction model based on MIESM for iterative minimum mean squared error (MMSE) interference cancellation detection. Experimental results for this method for an LTE-compliant system are shown in [12]. Another important work was presented in [13] for MIMO-OFDM systems with maximum likelihood (ML) receivers. Their model is also based on a variant of MIESM (based on work by [5]) and they model the effects of channel mismatch and correlation in the abstraction model. They show results for the rate compatible punctured convolution codes and different MIMO antenna configurations. A new method for PHY abstraction for multi-user MIMO (MU-MIMO) in the framework of LTE using non-linear interference aware receivers has been proposed in [14]. Although the scheme is targeted towards MU-MIMO systems but it can also be applied to MIMO systems employing non-linear receivers.

B. PHY abstraction in LTE systems

The 3GPP long-term evolution (LTE) is a 4th generation cellular communications standard. On the downlink (DL), LTE employs orthogonal frequency division multiple access (OFDMA) and defines several physical transport channels. The most important one, the physical downlink shared channel (PDSCH) uses turbo-codes with adaptive modulation and coding as well as hybrid automatic repeat request (HARQ) protocol. The PDSCH can also make use of MIMO techniques through the so called transmission modes. For example, transmission mode 2 refers to Alamouti precoding, while transmission mode 4 means closed-loop spatial multiplexing with up to two spatial streams. The challenge for PHY abstraction for the PDSCH is to have a system that can flexibly adapt to the different code rates and takes into account the HARQ and the MIMO transmission mode.

In addition to the PDSCH, the downlink also defines a physical control channel (PDCCH), which uses a variable rate tail-biting convolutional code and the physical broadcast channel (PBCH), which uses a fixed rate turbo code.

On the uplink (UL), LTE uses single carrier frequency division multiple access (SC-FDMA) and defines the physical uplink shared channel and the physical uplink control channel. The first one uses–like the downlink–adaptive turbo codes, while the latter uses either simple spreading codes for small payloads (format 1, 1a, and 1b) or Reed-Muller linear codes for larger payloads (format 2, 2a, 2b).

In the following chapter we describe the abstraction procedure for the PDSCH.

C. PHY Abstraction Overview

In the following we give a brief overview of the PHY abstraction process based on effective SINR mapping (ESM). The procedure can be divided into three steps as shown in Figure 2: SINR calculation, SINR Compression, and Link Quality Mapping.

SINR calculation: The first step of the PHY abstraction procedure consists of the SINR calculation per resource element (RE). This step depends on the transmission mode and the used receiver architecture. The most simple case is transmission mode 1 (SISO), where the signal model is given by

$$y_n = h_n \cdot x_n + z_n, \quad n = 0, \dots, N-1 \tag{1}$$

where $x_n \in \chi_M$ are the modulated resource elements (RE) of the encoded codeword, taken from a finite constellation of order M (QPSK, 16QAM, or 64QAM), h_n is the channel at RE n, y_n is the received signal at RE n, and z_n is the circularly symmetric additive white Gaussian noise (AWGN) with zero mean and variance σ^2. N is the total number of REs occupied by the codeword. The SINR γ_n is for every RE $n = 0, \dots, N-$

1 is then given by

$$\gamma_n = \frac{|h_n|^2}{\sigma^2}, \quad n = 0, \dots, N-1. \tag{2}$$

Transmission mode 2 uses Alamouti precoding on two transmit antennas to achieve transmit diversity. In the first symbol time x_1 and x_2 are transmitted from antenna 1 and 2, whereas in the second symbol time $-x_2^*$ and x_1^* are transmitted from antenna 1 and 2 respectively. At the receiver, the two received signals are combined and the SINR for the n-th resource element is given by

$$\gamma_n = \frac{||\mathbf{H}_n||^2}{2\sigma^2}, \tag{3}$$

where $\mathbf{H}_n$ is the MIMO channel at RE n.

Beamforming is implemented in LTE in transmission modes 6 and 7. The signal model for these modes is given by

$$\mathbf{y}_n = \mathbf{H}_n \mathbf{p}_n \cdot x_n + \mathbf{z}_n, \quad n = 0, \dots, N-1, \tag{4}$$

where $\mathbf{p}_n$ is the beamforming (precoding) vector. The SINR per RE at the receiver is given by

$$\gamma_n = \frac{||\mathbf{H}_n \mathbf{p}_n||^2}{\sigma^2}. \tag{5}$$

Closed loop spatial multiplexing is implemented in LTE in transmission modes 4, 8, and 9. A general signal model for those transmission modes can be written as

$$\mathbf{y}_n = \mathbf{H}_n \mathbf{P}_n \cdot \mathbf{x}_n + \mathbf{z}_n, \quad n = 0, \dots, N-1, \tag{6}$$

where $\mathbf{x}_n = [x_{1,n}, \dots, x_{C,n}]^T$ is the vector of codewords and $\mathbf{P}_n = [\mathbf{p}_{1,n}, \dots, \mathbf{p}_{C,n}]$ is the precoding matrix. The SINR depends on the receiver architecture and has to be computed for each codeword c. In the ideal case, where the receiver is able to do perfect interference cancellation we would have

$$\gamma_{n,c}^{\text{PIC}} = \frac{||\mathbf{H}_n \mathbf{p}_{c,n}||^2}{\sigma^2}. \tag{7}$$

If an MMSE receiver architecture is used, then

$$\gamma_{n,c}^{\text{MMSE}} = \frac{1}{\left[\left(\mathbf{I} + \frac{1}{\sigma^2}\mathbf{p}_{c,n}^H \mathbf{H}_n^H \mathbf{H}_n \mathbf{p}_{c,n}\right)^{-1}\right]_{c,c}} - 1. \tag{8}$$

For maximum-likelihood receivers, [13] has recently shown that the SINR can be modeled as

$$\gamma_n^{\text{ML}} = (1 + \gamma_{n,c}^{\text{PIC}})^{\alpha\beta}(1 + \gamma_{n,c}^{\text{MMSE}})^{1-\alpha\beta}, \tag{9}$$

where α and β are factors that need to be calibrated in advance.

Multi-user MIMO (transmission modes 5 or 9) is a special case of the above, where different codewords are destined for different users. Here the signal model can be written as

$$\mathbf{y}_n = \mathbf{H}_{1,n}\mathbf{p}_{1,n} \cdot x_{1,n} + \mathbf{H}_{1,n}\mathbf{p}_{2,n} \cdot x_{2,n} + \mathbf{z}_n, \quad n = 0, \dots, N-1, \tag{10}$$

where the first term is the desired signal for user 1 and the second term is the interfering signal destined for user 2. A standard or interference unaware (IU) receiver would treat the interfering signal as noise and thus the SINR would be given by

$$\gamma_{n,c}^{\text{IU}} = \frac{||\mathbf{H}_n \mathbf{p}_{1,n}||^2}{||\mathbf{H}_n \mathbf{p}_{2,n}|| + \sigma^2}. \tag{11}$$

A more intelligent, interference aware (IA) receiver (such as the one described in [15]) however is able to take this interference into account and perform optimal detection. In this case the abstraction procedure is a bit different since instead of the SINR we now need to calculate the signal to noise ratio (SNR) and the signal to interference ratio (SIR) separately. Please refer to [14, 16] for details.

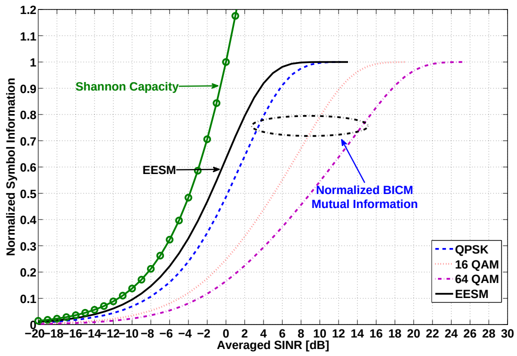

Fig. 3. Comparison of different information mapping functions.

SINR Compression: Secondly, the multi-state channel described by the post-processing SINR $\gamma_n, n = 0, \dots, N-1$ is compressed into a single *effective* SINR value γ_{eff} using an information measure function I:

$$\gamma_{\text{eff}} = \beta_1 I^{-1}\left[\frac{1}{N}\sum_{n=1}^{N} I\left(\frac{\gamma_n}{\beta_2}\right)\right]. \tag{12}$$

β_1 and β_2 are called an adjustment factor that need to be calibrated [16, 17]. The reverse information mapping function I^{-1} does not necessarily have to be the same as the forward function I, for example if the interference aware receiver abstraction is used [14].

For turbo codes, several choices for the information mapping function I are available (other codes might require other functions):

EESM. The exponential effective SINR mapping (EESM) function is calculated using Chernoff union bound of error probabilities, i.e.,

$$I_{\text{EESM}}(\gamma_n) = 1 - \exp(-\gamma_n) \tag{13}$$

MIESM. The mutual information based effective SINR mapping (MIESM) function is on the mutual information of bit-interleaved coded modulation (BICM) [18].

$$I_{\text{MIESM}}(\gamma_j, M_1) = \log M_1 - \frac{1}{M_1}\sum_{x_1 \in \chi_1} \mathcal{E}_{z_1} \log \frac{\sum_{x_1' \in \chi_1} \exp\left[-\left|\gamma_j\left(x_1 - x_1'\right) + z_1\right|^2\right]}{\exp\left[-|z_1|^2\right]}, \tag{14}$$

	Full PHY	Abstraction
Throughput	1.75 Mbps	1.73 Mbps
BLER	4%	4%

TABLE II. SYSTEM PERFORMANCE FOR FULL PHY AND ABSTRACTION.

	Full PHY	Abstraction	Improvement
UE TX	0.035	0.010	4
UE RX	0.493	0.026	19
eNB TX	0.157	0.012	13
eNB RX	0.077	0.012	6
UL channel	1.982	n/a	n/a
DL channel	2.313	0.012	192
total	5.056	0.072	70

TABLE III. SIMULATION TIMES PER SUBFRAME (IN MS) FOR FULL PHY AND ABSTRACTION.

where χ_1 is the set of constellation points, $M_1 = |\chi_1|$ is the modulation order, and z_1 is a circularly symmetric white Gaussian noise with zero mean and unit variance.

A comparison of the information mapping functions is given in Figure 3. Note that we plot the MIESM functions in a normalized way to allow a better comparison with the EESM function. It can be seen that the EESM function is a good approximation and advantageous due to its simplicity. However, best results are achieved with the mutual information function. The only problem is these functions need to be pre-computed using Monte-Carlos simulations since no closed form expressions exist.

Link Quality Mapping: The final step of PHY abstraction computes the block error rate (BLER) of the channel as a function of the effective SINR γ_{eff} based on pre-computed AWGN reference curves for the effective coderate of the codeword r_{eff}, and the modulation order Q_m.

$$\text{BLER} = \text{BLER}_{\text{AWGN}}(r_{\text{eff}}, \gamma_{\text{eff}}, Q_m) \quad (15)$$

The number of reference curves can be reduced to three (one per modulation order) by appropriate shifting of the curve according to the effective code rate r_{eff} [10]. This method is also applicable to HARQ.

III. PERFORMANCE RESULTS

Both EESM and MIESM abstraction methodologies have been implemented in the OpenAirInterface LTE system level simulator (oaisim). In this section we analyze the applicability and the performance of MIESM compared to a full PHY implementation (EESM has already been analyzed in [17]). The simulation parameters used in this experiment[1] are the same as in Table I. Table II shows a comparison of the throughput and their (BLER) for both the full PHY and the PHY abstraction. As expected, the PHY abstraction shows the same performance results as the full PHY, proving the applicability of the method.

Table III shows the simulation times per subframe (in ms) for full PHY and abstraction and the corresponding improvements factors. It can be seen that the abstraction provides performance improvements in the execution of both UE and eNB, but the most notable performance improvement is in the DL channel, since in the abstraction we do not need to carry out the channel convolution. The UL channel is not yet abstracted in oaisim (it is error free regardless of the channel), so the performance numbers are not yet available. However, the same numbers as for the DL can be expected. Figure 4 depicts an extrapolation of the execution time for a multi-user system. It can be seen that asymptotically a factor 100 can be saved in execution time, allowing the simulation of a 20 user system almost in real-time on a single core CPU.

[1]The code used for this experiment has been tagged on our SVN server and can be found at http://svn.eurecom.fr/openair4G/tags/asilomar2013.

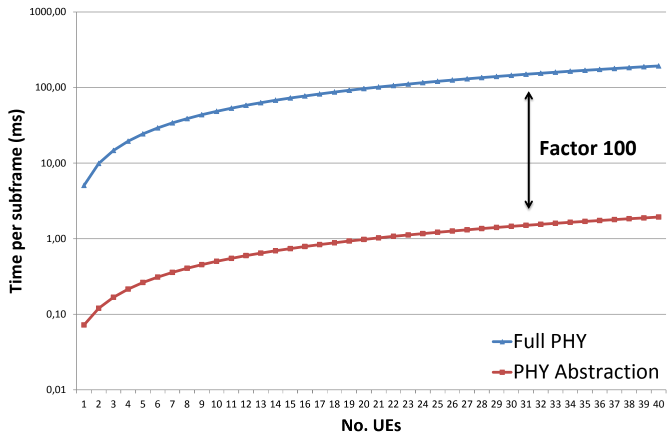

Fig. 4. Comparison of the computation time of the system level simulator with full PHY and with abstraction.

IV. CONCLUSIONS

We have shown in this paper that the physical layer and channel model take more than 80% of simulation time in state-of-the-art LTE system level simulators. To simulate large systems with several base stations and hundreds of users, the simulation time becomes prohibitively complex. Physical layer abstraction is a technique to predict the performance of a physical link without running the complex MODEM and the channel convolution. We have shown with the help of the OpenAirInterface system level simulator oaisim, which implements LTE release 8/9 both with full PHY and PHY abstraction, that PHY Abstraction can improve simulation time by a factor of 70 for a single link and by a factor of 100 for a multi-user system.

ACKNOWLEDGMENT

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