Link Abstraction for Multi-User MIMO in LTE using Interference-Aware Receiver

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***Abstract*—Recent wireless communication systems are interference limited rather than noise limited. In case of a very strong interferer the conventional assumption of interference as Gaussian is extremely suboptimal. However optimal receivers utilize some prior knowledge about interference to reach optimality and the link abstraction for such receiver structures is not studied well. We investigate how the conventional link abstraction technique can be extended for accurate and efficient link performance modeling for the low complexity optimal receivers. We discuss some of the most studied link abstraction schemes for an optimal low complexity interference aware receiver for multi-user MIMO in the frame work of LTE. We show the accuracy of discussed abstraction methods with the help of results from the Eurecom's link level simulator which implements LTE Release 8.**

I. Introduction

Baseline specifications of 3GPP's Long Term Evolution (LTE) system offers at least 100Mbits/s of data rate at the downlink and 50Mbits/s at the uplink. These are the data rates which were only possible on the wired networks almost only a decade ago. But today LTE is being deployed in some parts of the world making such high data rates possible for wireless cellular communications. The applications of high speed wireless cellular communications are in almost all fields of life, i.e., medical, defense, business and not to forget the social life. Considering the combination of smart phones, tablets, netbooks, online social media and cloud computing the need for higher data rates is on the rise more than ever. That is why the latest release of LTE named as LTE-Advanced (LTE-A) is targeting the data rates of 1 Gbits/s on the downlink and 500 Mbits/s on the uplink.

The key technology in LTE and LTE-A is the use of multiple antennas at the transmitter and receiver. The gains offered by the use of multiple antennas in LTE can come from spatial multiplexing, spatial diversity and/or precoding. MIMO systems generally fall into two categories, single-user (SU) MIMO and multi-user (MU) MIMO. As compared to SU MIMO, MU-MIMO has lots of potential [1] and can be highly spectral efficient by serving more than one user for the same time and frequency resource. The gains offered by MU-MIMO on the single communication link do not necessarily represent the same gains when deployed in a huge system. Therefore the system level evaluations are necessary to be performed before its deployment. In system level simulations multiple base stations communicate with multiple users thus representing small cities or some parts of big cities. The realistic evaluations should not only account for the benefits of the more sophisticated techniques but also should be able to reflect the effect of different kind of interferences in the network. Implmentation of MU-MIMO suffers highly from multi-user interference. It is shown in [16] that for LTE release 8 MU-MIMO does not meet the expectations of theoretical gains even with ideal channel estimation and no multi-user interference at all. This is because LTE Release 8 is optimized for SU-MIMO only and does not provide any optimized feedback strategy and codebooks for MU-MIMO.

However, system level evaluations normally require heavy computations for extremely long duration of time because of the characterization of the radio links between each user and base station. The link level simulations of all such links is the bottle neck in these evaluations. Therefore, to reduce the complexity and duration of system level simulations we need to have an accurate link abstraction model which replaces the actual link level computations and provides the higher layers with necessary and accurate link quality metric, i.e., block error rate (BLER). Link abstraction is an extremely valuable low complexity tool for efficient large scale system evaluations. Moreover it can also be used for fast resource scheduling, fast link adaptation using adaptive power control and adaptive modulation and coding (AMC).

This paper presents analysis of the link abstraction for interference limited systems where the low complexity optimal receivers are used. The low complexity receivers normally use some prior knowledge about either interference itself or about its structure to reach the optimality. As an example we perform the link abstraction for MU-MIMO in LTE release 8 where the link abstraction predicts the performance of a low complexity interference aware receiver.

Rest of the paper is organized as follows: In section II we present link abstraction and state of the art for link abstraction. In section III we present an overview of MU-MIMO in LTE

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Release 8 and present mutual information under interference for MU-MIMO. In section IV we present the link abstraction for MU-MIMO in detail. Then section V presents results along with the methodology for training and testing the proposed abstraction technique. Finally in section VI we present the conclusion.

II. Link Abstraction

The purpose of link abstraction is to provide an accurate mapping between the link level and system level simulator in terms of the link quality measure. For MIMO-OFDM systems the process of link abstraction can be defined as the process which predicts the link quality (in terms of BLER) for a specific channel realization across all of the OFDM sub-carriers and spatial layers taking into account the power and resource allocation, modulation and coding scheme (MCS) and other parameters that can influence the link performance. These other parameters mainly include channel characteristics, i.e., path loss, shadowing, fading and interference. The use of Link abstraction in system evaluations is explained in figure 1.

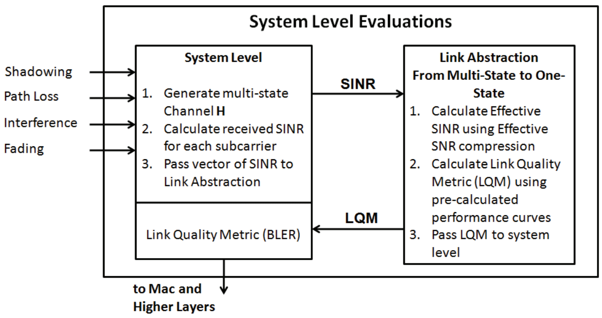

Fig. 1. Link Abstraction in System Performance Evaluation

Performance evaluation for frequency flat channels is trivial but for highly frequency selective channels the performance evaluation is not that straight forward and many link abstraction techniques have been proposed in the literature for these "multi-state" channels. [2][3][4] discuss the possible link performance models which are capable of capturing the effects of the "multi-state" channels. Exponential effective SINR mapping (EESM) was first introduced in system level evaluations in [2] and since then onwards have been extensively used for link quality modeling. In [5] it is shown that EESM is a suitable choice for 3GPP LTE wireless systems and it performs better than other link quality schemes but mutual-information based methods were not considered for the comparison. They also showed through simulations that training of link abstraction is independent of the used channel model. In [3] authors discussed some of the possible link performance models and evaluated them in terms of complexity and performance. They showed through their results that for single antenna systems mutual-information based effective SINR mapping (MIESM) performs better in both complexity and performance than all other approaches. They also showed that for multi-antenna system MIESM is able to describe the characteristics of modulation and coding schemes in a much better way than other schemes. In [6] authors have introduced one more calibration factor for EESM and shown that it speeds up the abstraction process. In [7] authors have studied the abstraction for generalized spatial channel model (SCM) and in [8] abstraction for OFDM based mobile networks is discussed. In [4] 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. They showed the superiority of MIESM over EESM using this approach as well. This result was strengthened by [9] (Wireless World Initiative New Radio- WINNER) and they chose MIESM as the link performance modeling methodology. An interesting result is shown in [10] which states that the training for the link quality model of MIMO systems should not be done using SISO systems. They strengthen their point by showing results for 2x2 open loop MIMO system using both EESM and MIESM and they have also shown that MIESM performs better than EESM.

The two most studied link abstraction methodologies are the expected effective SINR mapping (EESM) and mutual-information based effective SINR Mapping (MIESM). In both of the two methods the basic scheme is effective SINR mapping which at first maps the varying SINRs of a codeword to an effective SINR (γ_{eff}) value which is then used to read the equivalent BLER from the AWGN performance curves of a particular modulation and code scheme (MCS).

$$\gamma_{eff} = \delta_1 I^{-1}\left[\frac{1}{J}\sum_{j=1}^{J} I\left(\frac{\gamma_j}{\delta_2}\right)\right] \tag{1}$$

$$\gamma_{eff} \rightarrow BLER(mcs) \tag{2}$$

Where J is the number of channel symbols in a codeword and $I(\gamma_j)$ is a mapping function which transforms SINR of each channel symbol to some "information measure" where it is linearly averaged over the codeword. Then these averaged values are transformed back to SNR domain. δ_1 and δ_2 are called calibration factors and they are there to compensate for different modulation orders and code rates.

For the EESM the mapping function $I(\gamma_j)$ is calculated using Chernoff Union bound of error probabilities[2], i.e.,

$$I(\gamma_j) = 1 - \exp(-\gamma_j) \tag{3}$$

$$\gamma_{eff} = -\beta \ln\left[\frac{1}{J}\sum_{j=1}^{J} \exp\left(-\frac{\gamma_j}{\beta}\right)\right] \tag{4}$$

Normally for EESM $\delta_1 = \delta_2 = \beta$ and it needs to be adjusted for each MCS. whereas for the mutual information based methods the approximations of mapping function and the reverse mapping functions come from the mutual information for discrete QAM constellation, i.e.

$$I_{M_1}(\gamma_j) = \log M_1 - \frac{1}{M_1} \sum_{x_1 \in \chi_1} \mathcal{E}_{z_1} \log \frac{\sum_{x_1' \in \chi_1} \exp\left[- \left| \gamma_j \left(x_1 - x_1' \right) + z_1 \right|^2 \right]}{\exp\left[- |z_1|^2 \right]} \quad (5)$$

where χ_1 is the set of the QAM constellation points with $|\chi_1| = M_1$ and $z_1 \in \mathcal{CN}(0,1)$.

III. Multi-User MIMO in LTE using Interference Aware Receiver

LTE Release 8 was standardized generally to benefit from SU-MIMO, so the support for MU-MIMO (LTE transmission mode 5) was added only at a very basic level in it. In LTE transmission mode 5, eNB schedules two users during the same time and frequency resource so it requires a very sophisticated channel state information at transmitter (CSIT) in order to provide independent parallel channels from cross coupled channels (i.e., eliminating multi-user interference). But in LTE Release 8 the rank indicator (RI) and precoding matrix indicator (PMI) feedback are the same as for SU-MIMO rank 1 and it only contains four precoders, $\mathbf{p} = [1 \quad q]^T, \quad q \in \{\pm 1, \pm j\}$, which are extremely low resolution needing merely 2 (for 2 antenna ports) to 4 (for 4 antenna ports) bits of feedback from the users. On top of this low resolution precoding comes the overhead of quantization and feedback delays which even after using the optimal scheduling for selected users significantly degrades the performance of MU-MIMO in LTE Release 8. A way forward to achieve the gains of MU-MIMO in LTE Release 8 is to employ interference aware receivers, as was shown in [11] and [12]. Therefore, we use interference aware receivers for MU-MIMO in LTE Release 8 and schedule the two UEs who request opposite precoders from eNodeB.

a) Mutual information under interference: The detailed mutual information expressions for a MU MIMO system employing such a receiver are given in [11] which will subsequently be used in our abstraction model. We assume LTE baseline configuration, where a dual-antenna eNodeB communicates with 2 single-antenna UEs. The received signal at the desired user (say UE-1) on n-th resource element is given by

$$y_{1,n} = \mathbf{h}_{1,n}^{\dagger} \mathbf{p}_{1,n} x_{1,n} + \mathbf{h}_{1,n}^{\dagger} \mathbf{p}_{2,n} x_{2,n} + z_{1,n}, \quad n = 1, 2, \cdots, N$$

where $\mathbf{h}_{1,n}^{\dagger} \in \mathbb{C}^{2\times 1}$ symbolizes the MISO channel from the eNodeB to UE-1, $\mathbf{p}_{k,n}$ is the precoder requested by k-th UE and $z_{1,n}$ is ZMCSCG white noise of variance N_0 at UE-1. Complex symbols $x_{1,n}$ and $x_{2,n}$are assumed to be independent and of variances σ_1^2 and σ_2^2 respectively. These symbols belong to discrete QAM constellations, i.e. $\chi_{1,n}$ and $\chi_{2,n}$ respectively. The dependency on the resource element index can be ignored, since the processing is assumed to be performed on a resource element basis for each received OFDM symbol. Moreover we denote the effective channels as $\alpha_1 = \mathbf{h}_1^{\dagger} \mathbf{p}_1$ and $\zeta_2 = \mathbf{h}_1^{\dagger} \mathbf{p}_2$. The mutual information expression for desired user in such a system is given by (6). In [11] the authors have shown that optimal low complexity interference aware receiver can actually be implemented achieving (6). The mutual information can be numerically calculated using sampling (Monte-Carlo) methods with N_z realizations of noise and N_h realizations of the channel $\mathbf{h}_1^{\dagger}$. The precoder is selected based on the channel realization and is therefore not random. Similarly we can write the mutual information expression for UE-2.

IV. Abstraction for Multi-User MIMO

In case of EESM, SINR for each subcarrier (γ) is calculated using (4) and an effective SINR (γ_{eff}) is calculated for the given codeword. Based on this γ_{eff} the equivalent BLER from the pre-calculated AWGN perofrmance curves corresponding to the specific MCS is obtained and given to the system level simulators. The methodology for MI-based abstraction is given in more details here.
We present an extension of the mutual information based abstraction methodology of [4] for the link abstraction of interference aware receivers and normal receivers.

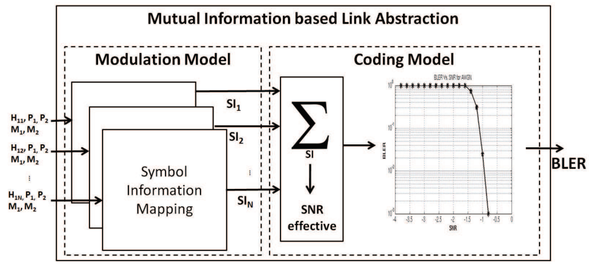

Fig. 2. Mutual information based abstraction model

The abstraction model consists of two blocks, modulation model and coding model as shown in figure 2. The inputs for the abstraction can be SINR values for each subcarrier or the channel of desired user, precoder and constellation of desired and interfering user. Based on the preffered input the modulation model calculates maximum channel capacity in terms of symbol information for every subcarrier. The modulation model only accounts for the modulator and demodulator. Then in the coding model symbol information of each subcarrier belonging to the same codeword is averaged over total number of transmitted bits during that codeword to reach the received bit information rate (RBIR). This RBIR is used to read the effective SNR from SNR-to-normalized SI mapping. Then finally this effective SNR is used to read the BLER from previously calculated AWGN performance curves corresponding to the specific MCS.

A. Modulation Model

Modulation model as shown in figure 2 provides us with the symbol information (SI) in terms of maximum channel capacity for each of the subcarrier. In this report we propose two modulation models for the specific case of MU-MIMO.

1) Modulation Model 1: The first modulation model is based on (6) and is stored in the form of a look up table. This table is a function of the modulation order of the desired stream ($M1$) and the interfering stream ($M2$), the signal to

$$I\left(Y;X_1|\alpha_1,\zeta_2\right)=\log M_1-\frac{1}{M_1M_2N_zN_h}\sum_{x_1}\sum_{x_2}\sum_{\mathbf{h}_1^{\dagger}}^{N_h}\sum_{z_1}^{N_z}\log\frac{\sum_{x_1'}\sum_{x_2'}\exp\left[-\frac{1}{N_0}\left|\alpha_1x_1+\zeta_2x_2+z_1-\alpha_1x_1'-\zeta_2x_2'\right|^2\right]}{\sum_{x_2''}\exp\left[-\frac{1}{N_0}\left|\zeta_2x_2+z_1-\zeta_2x_2''\right|^2\right]} \tag{6}$$

noise ratio (SNR) of the desired stream, desired signal $|\alpha_1|$ and interference $|\zeta_2|$. Since the purpose of link abstraction is to reduce complexity so table for symbol information mapping should be available as a look-up. To generate these tables we performed Monte-Carlo simulations of (6) over a wide range of noise and channel realizations. For each channel realization we obtained a random set of $|\alpha_1|$, $|\zeta_2|$ and mutual information. For all other required values this scatter-plot was interpolated using linear interpolation. As an example an interpolated graph for the SNR of 10 dB is shown in figure(3) where on the x-axis is the signal strength, on y-axis is the interference strength and on z-axis is the mutual information.

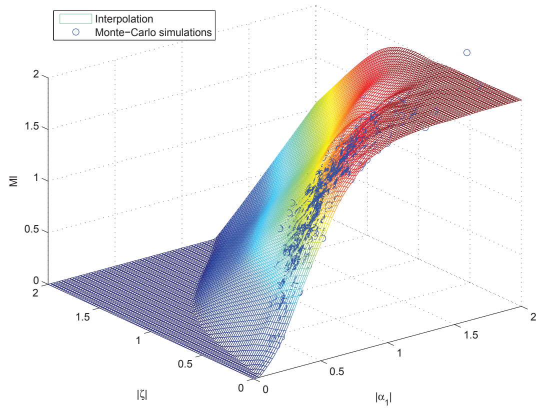

Fig. 3. MI for SNR of 10 dB

2) Modulation Model 2: The second modulation model is based on (5), the mutual information expression for the discrete constellation for a single user case where the interference from the interfering user is conisdered as gaussian and is conisdered in noise for SINR calculation.

B. Coding Model

The coding model corresponds to the encoding and decoding of the codeword and predicts the performance for whole codeword. The output of modulation model is a vector of symbol informations for all of the subcarriers of a codeword. The first thing which coding model calculates is the collection of received coded bit information (RBI) for the desired user among J subcarriers,

$$RBI=\sum_{j=1}^{J}\frac{SI\left(\|\alpha_{1,j}\|,\|\zeta_{2,j}\|,M_{1,j},M_{2,j}\right)}{\beta} \tag{7}$$

Where the first index in modulation order $M_{i,j}$ represents the user and second index represents the subcarrier. β is an adjusting factor which compensates of practical coding loss. The optimal value of β can be trained over a set of enough channel realizations that covers a reasonable amount of different channel variations. RBI is then normalized by the number of total coded bits to the received bit information rate (RBIR),

$$RBIR=\frac{RBI}{\sum_{j=1}^{J}M_{1,j}} \tag{8}$$

As is shown in figure 4 RBIR can also be regarded as normalized SI and is used for calculating the effective SINR. Then this effective SINR is used to obtain BLER from the equivalent AWGN performance curve for a specific MCS. These AWGN curves are pre-calculated for all MCS of LTE and stored in the form of a look-up table.

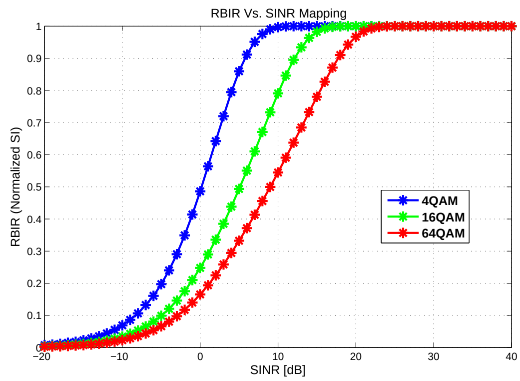

Fig. 4. RBIR Vs. SINR Mapping

V. Results

In order to train and test the proposed MU-MIMO link abstraction for interference aware receivers and normal receiver, we used Eurecom's OpenAirInterface[1] simulator which implements 3GPP LTE Release 8.6 physical layer [13], [14], [15] with 5 MHz bandwidth and 25 physical resource blocks (PRB). It uses TDD UL/DL Frame Configuration 3 where there are 6 downlink (DL) subframes, 3 uplink (UL) subframes and a special subframe with configuration 0 (i.e., longest guard interval). Both normal and extended cyclic prefix can be used in simulator and it deploys OFDMA on the downlink and OFDMA or SC-FDMA on the uplink. It uses rate 1/3 turbo encoder and one can perform simulations for all of the LTE MCS (0-28) for different types of channels. Both ideal and real channel estimations can be performed in it as well. For MU-MIMO we considered the case where there were 2 TX antenna ports at eNodeB and 1 at UE. It can perform different LTE

[1] http://www.openairinterface.org/

transmission modes i.e. LTE Transmission Mode 1 (SISO), 2 (Transmit Diversity), 5 (Multi-User MIMO) and 6 (Closed loop single-user MIMO with single-layer precoding). It also deploys aperiodic feedback where there is subband PMI and wideband CQI. Also HARQ is also implemented for all these transmission modes in Eurecom's OpenAirInterface simulator. We performed link abstraction of MU-MIMO for the 8-tap Rayleigh channel model using real channel estimation for interference aware receiver (IA) and normal receiver. We performed simulation for 70 different channel realizations and during each of channel we simulated the system for 10000 packets or 100 erroneous packets. We saved the BLER and other required parameters which were necessary for link abstraction. The we applied the EESM and MI-based link abstraction of section IV on the saved output of simulations. The solid line represents the AWGN curve whereas the red diamonds show the points which are mapped on AWGN using link abstraction methodology.

A. EESM

Results of abstraction using Eurecom's OpenAirInterface simulator for the multi-user MIMO for LTE mcs 7 and 9 using EESM are shown in figure 5-8.

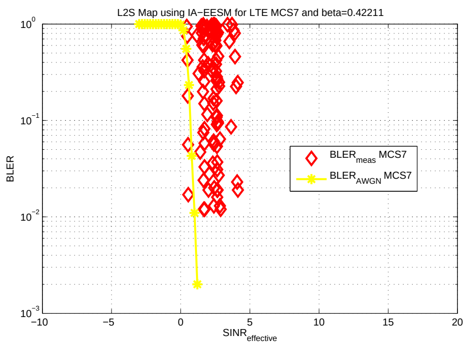

Fig. 5. IA Receiver: Multi-user MIMO abstraction using EESM for LTE MCS 7 with 8-tap Rayleigh Channel Model

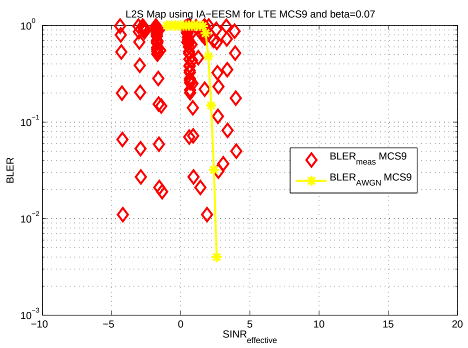

Fig. 6. IA Receiver: Multi-user MIMO abstraction using EESM for LTE MCS 9 with 8-tap Rayleigh Channel Model

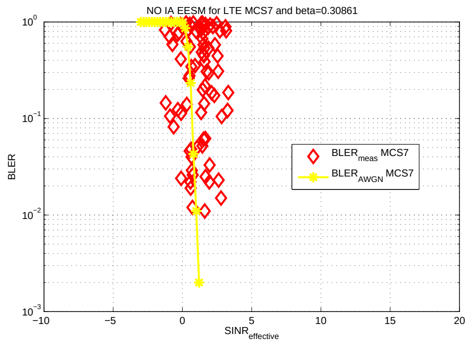

Fig. 7. Normal Receiver: Multi-user MIMO abstraction using EESM for LTE MCS 7 with 8-tap Rayleigh Channel Model

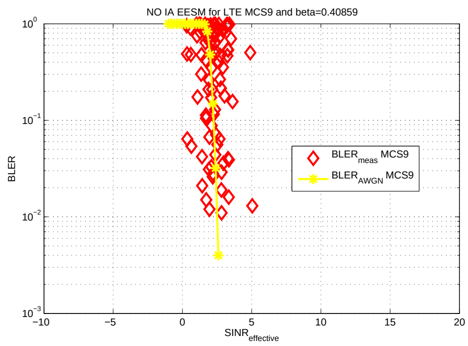

Fig. 8. Normal Receiver: Multi-user MIMO abstraction using EESM for LTE MCS 9 with 8-tap Rayleigh Channel Model

B. MI-based Modulation Model 1

Results of abstraction using Eurecom's OpenAirInterface simulator for the multi-user MIMO for LTE mcs 7 and 9 using MI-based abstraction with **Modulation Model 1** are shown in figure 9-12.

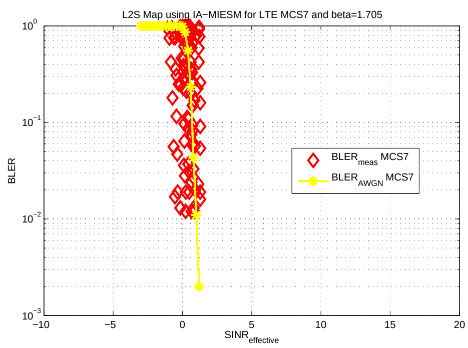

Fig. 9. IA Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 7 with 8-tap Rayleigh Channel Model

C. MI-based Modulation Model 2

Results of abstraction using Eurecom's OpenAirInterface simulator for the multi-user MIMO for LTE mcs 7 and 9 using

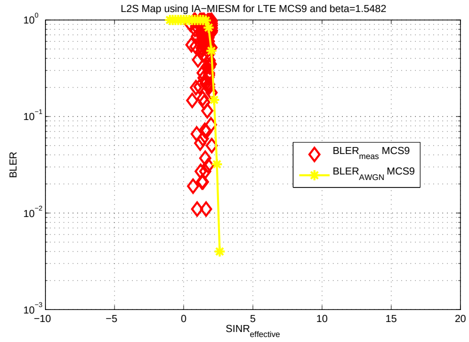

Fig. 10. IA Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 9 with 8-tap Rayleigh Channel Model

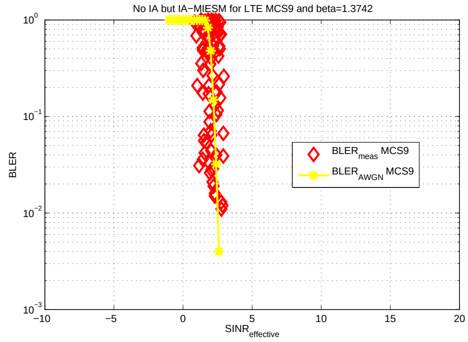

Fig. 12. Normal Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 9 with 8-tap Rayleigh Channel Model

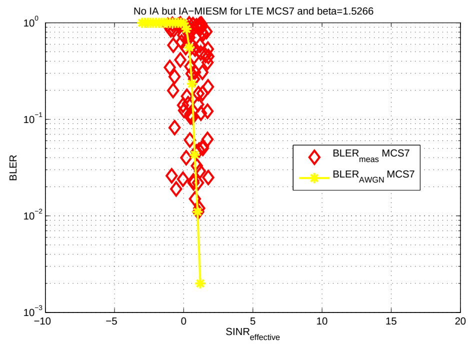

Fig. 11. Normal Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 7 with 8-tap Rayleigh Channel Model

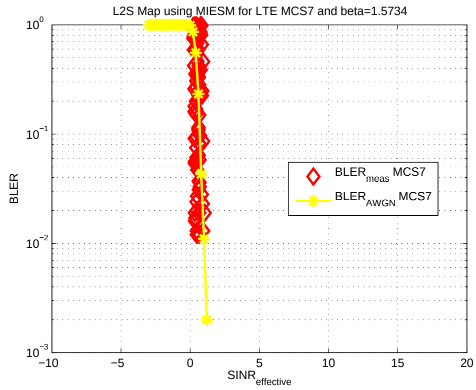

Fig. 13. IA Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 2 for LTE MCS 7 with 8-tap Rayleigh Channel Model

TABLE I
MEAN SQUARED ERROR (MSE) VALUES FOR MU-MIMO ABSTRACTION

Technique	**MCS7**	**MCS9**
IA-EESM	0.2964	0.2109
Normal-EESM	0.2819	0.2830
IA-MI-M1	0.2231	0.2048
Normal-MI-M1	0.2588	0.2421
IA-MI-M2	0.1440	0.1382
Normal-MI-M2	0.1879	0.1612

MI-based abstraction with **Modulation Model 2** are shown in figure 13-16.

In the following we present a table with the Mean Squared Error (MSE) Values for MU-MIMO abstraction using different abstraction techniques. We can see that MI-based abstraction for IA receiver with modulation model 2 gives us the best result.

It is clear from the results that the link abstraction is only accurate for the MI-based abstraction with modulation model 2. EESM gives the worst performance and MI-based abstraction with modulation model 1 is also not extremely accurate but better than EESM.

VI. CONCLUSION

In this paper we presented different methods through which the conventional link abstraction techniques can be extended for the link performance of optimal receivers. As an example we applied this link abstraction approach towards MU-MIMO in LTE Release 8 for the specific case of interference aware receiver using EESM and mutual information based abstraction with two different Modulation Models. The results showed the superiority of the mutual information based methods over EESM proving its importance for accurate and efficient system evaluations for both industry and academia.

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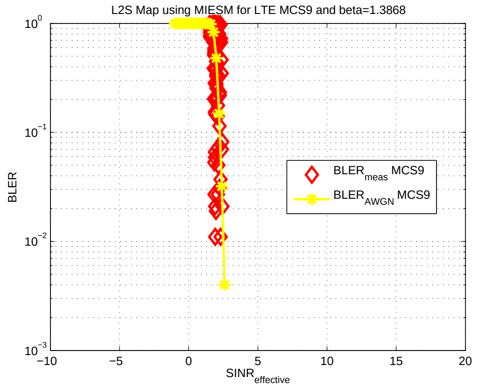

Fig. 14. IA Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 2 for LTE MCS 9 with 8-tap Rayleigh Channel Model

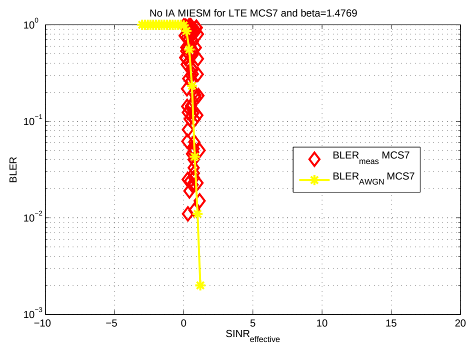

Fig. 15. Normal Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 7 with 8-tap Rayleigh Channel Model

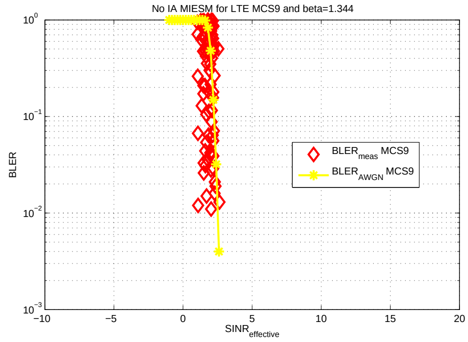

Fig. 16. Normal Receiver: Multi-user MIMO abstraction using MI-based abstraction Modulation Model 1 for LTE MCS 9 with 8-tap Rayleigh Channel Model

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