International Journal of Advanced Computer and Mathematical Sciences ISSN 2230-9624.
Vol 2, Issue 1, 2011, pp 58-65 http://bipublication.com

PERFORMANCE EVALUATION OF FAST LINK ADAPTATION ALGORITHM FOR OFDM SYSTEMS

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ABSTRACT

This paper investigate link quality metrics (LQMs) based on effective signal-to-interference-and-noise ratio, and mutual-information (MI) for the purpose of fast link adaptation in communication systems employing orthogonal frequency division multiplexing and multiple-input multiple output (MIMO) antenna technology. From these LQMs the packet-error-rate (PER) can be estimated and exploited to select the modulation and coding scheme (MCS) among various MCSs that achieves the maximum throughput for the current channel state under a specified target PER objective. We propose a novel MI-based LQM and compare the PER estimation accuracy obtained with this LQM with that resulting from using other LQMs by means of system level simulations. Search methods for the most suitable MCS among various MCS for a given channel state are presented. The investigated LQMs are applied to the IEEE 802.11n standard with a 2x2 MIMO configuration and practical channel estimation. The proposed MI-based LQM yields the highest PER estimation accuracy for the current noise variance.

Keywords—Adaptive modulation and coding, link adaptation, link quality metrics, channel state information, fading, feedback delay, OFDM, MIMO, PER estimation.

I. INTRODUCTION

The sub-carriers transmitted by a multiple-input multiple output (MIMO) orthogonal frequency division multiplexing (OFDM) system across a time-varying frequency-selective channel are received with a quality level that varies over time, frequency and spatial streams. This knowledge can be exploited in the transmitter to adjust the modulation and coding scheme (MCS) in such a way that high-order modulations and high coding rates are used in situations of good channel state. This can be accomplished by the receiver identifying, among an indexed list of candidate MCSs, the best MCS for the current channel state and feeding the index of this MCS back to the transmitter. It was shown in, *e.g.*, [1] that adaptive modulation and coding increases the throughput of a wireless communication system tremendously. The key elements in fast link adaptation (FLA) are estimation of the packet-error-rate (PER) for different candidate MCSs and selection of the MCS that maximizes the throughput with the constraint that the time average PER lies below a specified target value. FLA also includes a time critical aspect because the selection of the best MCS for the current channel state may become obsolete as this state changes. In systems employing MIMO OFDM antenna techniques, the main difficulty of PER estimation arises due to the unequal SNR levels in the different sub-carriers, as well as in the spatial streams when they are employed. This occurs since (i) the individual sub-carriers undergo different attenuations due to frequency selectivity and (ii) the ability of the receiver to separate multiple spatial streams depends on the condition-number of the MIMO channel matrix. The particular pattern of post-processing SINR values of the different sub-carriers induced by the channel state and the choice of the symbol detector strongly influences the decoder performance. However, the relationship between the post-processing SINR levels and the resulting bit-error-rate (BER) or PER after decoding cannot be expressed in a simple form [2]. Hence, one has to resort to a simple yet accurate mapping which provides an estimate of the PER as a function of the SINR levels.

The very same problem is of fundamental importance for system level simulations in cellular communications where the performances of a multitude of individual links are computed without actually simulating the transmission procedure of the individual bits. The latter approach would require too much computing effort to determine the overall system performance. The goal is to identify an appropriate physical layer abstraction that characterizes the instantaneous PER behavior of the MIMO-OFDM transceiver for the current state of the time and frequency-selective channel. In UMTS-technology, based on CDMA, the assumption is that the instantaneous post processing SINRs can be averaged (average value interface) or at least quantized using a few quantization levels [3]. This requires that the channel transfer function fades slowly versus frequency. Then the approach allows for accurate PER estimation results. However, in OFDM, multipath propagation causes a selective attenuation of the individual sub-carriers and, as a result, individual code symbols experience different SINRs. Hence, other methods have to be applied to supply reliable BER/PER estimation. One-dimensional mappings exhibit low complexity, while guaranteeing good performance [2] almost exhaust the maximal theoretical performance improvement and the additional gain achievable by using more complex techniques is minor. This motivates the interest in one-dimensional mappings in FLA.

Robust one-dimensional mappings have been widely studied in the literature, considering methods such as effective SNR [4], mutual-information (MI) [5], [6]. We propose a novel link quality metric (LQM) for MIMO-OFDM to be used for FLA. This paper compares mean MI bit mapping

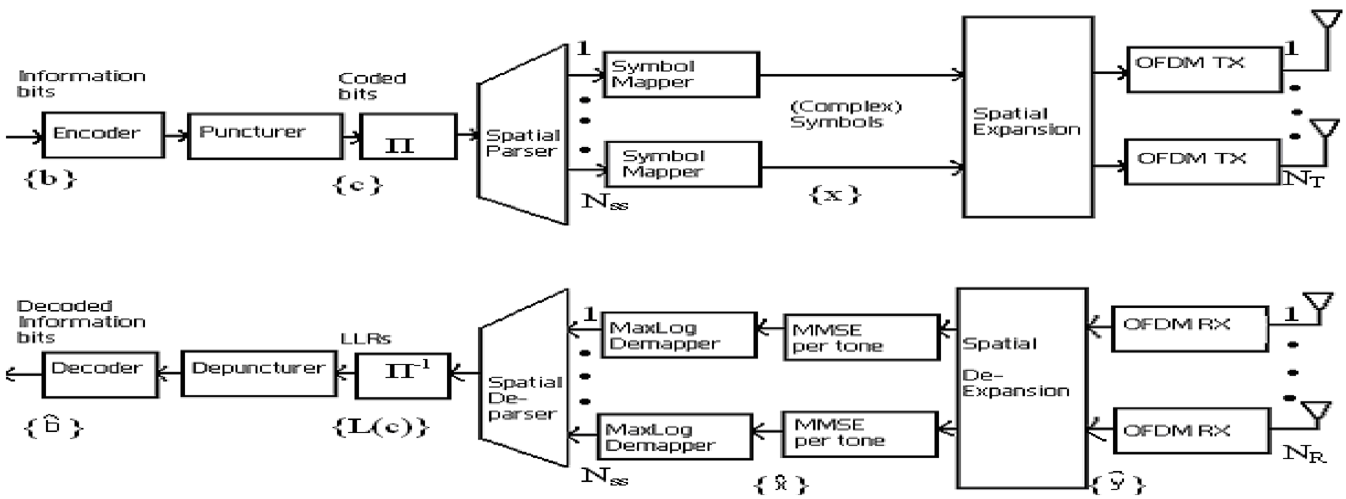

Figure.1 Block diagram of MIMO BICM-OFDM.

TABLE.1 LIST OF MCS FOR 2X2 MIMO-OFDM SYSTEMS

Index m	Sub-carrier modulation	Rc	Throughput [Mbps]	Index m	Sub-carrier modulation	Rc	Throughput [Mbps]
0(8)	BPSK	1/2	6.5 (13.0)	4(12)	16QAM	3/4	39.0 (78.0)
1(9)	QPSK	1/2	13.0 (26.0)	5(13)	64QAM	2/3	52.0 (104.0)
2(10)	QPSK	3/4	19.5 (39.0)	6(14)	64QAM	3/4	58.5 (117.5)
3(11)	16QAM	1/2	26.0 (52.0)	7(15)	64QAM	5/6	65.0 (130.0)

(MMIBM) with effective SNR (EESM). This paper assess the estimation accuracy of the two metrics for a large number of realizations of the (frequency) transfer function of frequency selective channels exhibiting different delay spreads also compares the effectiveness of these metrics by realistic throughput link-level simulations including channel estimation. The PER estimation accuracy, obtain an exact expression for the MI between the coded bits and the log-likelihood ratios (LLRs), and provide comparison among state-of-the-art PER estimation methods, as opposed to the less accurate instantaneous SNR method [2].

Notation

The Vectors denoted by bold lower case letters, *e.g.*, x, y, and matrices by bold upper case letters, *e.g.*, H, G. The conjugate transpose of the matrix A is denoted by AH. The element in the i-th row and j-th column of A is denoted as [A]i,j . The Q × Q identity matrix is written as IQ. The expectation operator is denoted by E {.} and C is the set of complex numbers.

II. SYSTEM MODEL

The IEEE 802.11n standard is a concrete example for the system model is depicted in Figure 1. This figure shows the simplified block diagram of a MIMO bit-interleaved coded modulation (BICM) OFDM system equipped with N_T transmit antennas and N_R receive antennas. In the IEEE 802.11n system, the information bit stream {b} is encoded using a convolutional encoder with generators [133, 171] in octal representation and basic code rate R_c = 1/2. The coded bit stream may be punctured to increase the code rate to 2/3, 3/4 or 5/6, depending on the used MCS. The stream of interleaved and spatially parsed bits is mapped to a stream of complex symbols using Gray mapping. Supported sub-carrier modulation formats are BPSK, QPSK, 16QAM and 64QAM. The candidate MCSs available are enumerated according to a certain order. In the sequel, Ω denotes the index set of the MCSs in this list. The available MCSs for single-stream and dual-stream transmission are listed with their index in Table 1. Their maximum throughput is reported in the columns “Throughput”. BICM schemes using different coding and modulation per stream in multi-stream transmission are given in [8].

The streams of complex symbols {x} are modulated in an OFDM format with N_{SD} = 52 data sub-carriers of 312.5 kHz bandwidth. The total bandwidth of the OFDM signal is 20MHz. The relationship for the k-th sub-carrier, k = 1, . . . ,N_{SD}, between the input of the spatial expansion scheme and the output of the OFDM receiver in Figure 1 is

$$y[k] = H[k]x[k] + n[k], \tag{1}$$

where y[k] Є C^{NR} and x[k] Є C^{NSS} are the received signal vector and the transmitted symbol vector respectively for subcarrier k and n[k] Є C^{NR} is a complex zero-mean Gaussian noise vector with covariance matrix $\sigma^2_n I_{NR}$. The variable N_{SS} denotes the number of spatial streams and H[k] Є $C^{NR\times NSS}$ describes the effective channel matrix, including the channel transfer function, the cyclic delay diversity (CDD) and the spatial expansion [14] for sub-carrier k. Spatial expansion transmits N_{SS} symbol streams over N_T transmit antennas, where $N_{SS} \leq N_T$. When spatial multiplexing is employed, $N_{SS} = N_T$. When either beam forming or Alamouti space-time coding is applied, $N_{SS} < N_T$. The CDD transmits a cyclicly delayed OFDM symbol waveform through each transmit antenna in order to obtain frequency diversity at the receiver side.

An unbiased linear minimum mean square error (MMSE) estimator is used to recover the transmitted symbol from the received signal y[k]:

$$\hat{x}[k] = G^H[k]y[k] \tag{2}$$

The $N_R \times N_{SS}$ matrix G[k] = [G_1 [k], G_2 [k], . . . G_{NSS} [k]] has columns given by

$$G_j[k] = \frac{1}{H_j^H[k]\left(H[k]H^H[k]+\sigma_n^2 I_{N_R}\right)^{-1} H_j[k]}\left(H[k]H^H[k]+\sigma_n^2 I_{N_R}\right)^{-1} H_j[k] \tag{3}$$

j = 1, 2, . . . ,N_{SS}, with H_j [k] denoting the columns of H[k], *i.e.*, H[k] = [H_1[k],H_2[k], . . . ,H_{NSS} [k]]. Notice that the linear biased MIMO-MMSE corresponds to (3) with the expression in the denominator set to one. The post-processing signal-to-interference-and-noise ratio (SINR) at the output of the linear MMSE estimator for the j-th stream and k-th tone OFDM is given by [6]

$$\gamma_j[k] = \frac{1}{\left[\left(\frac{E_S}{\sigma_n^2 N_T} H^H[k]H[k] + I_{N_{SS}}\right)^{-1}\right]_{j,j}} - 1$$

(4)

k = 1, 2, . . . ,N_{SD}, j = 1, 2, . . . ,N_{SS}, with E_s/σ_n^2 denoting the SNR measured at the ports of each receive antenna. A MaxLog symbol demapper is used to generate log-likelihood ratios (LLRs) for the coded bits, which are then multiplexed into a single stream {L(c)}. This stream is de-interleaved and de-punctured before it is fed to a Viterbi decoder that computes the information bit estimates $\{\hat{b}\}$. This paper focus on the case with $N_T = N_R$ = 2 antennas.

III. FAST LINK ADAPTATION

The objective of FLA is to exploit the varying channel state to increase the throughput of the system, while maintaining some target PER (PER_{target}). The FLA algorithm employed in the receiver feeds the index of the selected MCS back to the transmitter. This MCS feedback (MFB) response may occur based upon request from the transmitter.

The FLA algorithm considers the channel state information via the post-processing SINRs of all spatial streams and sub-carriers $\Gamma = [\gamma_j [k]]_{j=1,...,NSS;\ k=1,...,NSD}$. For a given MCS m, the FLA algorithm computes a scalar LQM value q = q (m;Γ). The PER value $PER_{m,p}(\Gamma)$ for packet length p corresponding to the current realization of the channel transfer function is estimated by $PER^{AWGN}_{m,p}$ (q), *i.e.*, the PER achieved when the MCS transmits across the AWGN channel with quality metric q. The latter mapping circumvents the need to store a look-up table of *PER*m,p(Γ) functions for some selected (quantized) SINR matrices. Indeed, the set of such quantized matrices required is large, which makes an implementation of this approach problematic.

Thus, for a given MCS m transmitting packets of length p across a channel inducing post-processing SINRs Γ, the LQM-to- PER mapping is determined such that the approximations hold.

$$PER_{m,p}(\Gamma) \approx PER_{m,p}^{AWGN}(q(m;\Gamma)) \approx \psi_{m,p}(q(m;\Gamma)) \tag{5}$$

For each MCS m Є Ω and packet length p of interest, the function $\psi_{m,p}(q)$ is computed considering two different channel quality metric, namely the SNR γ and the MI I of the AWGN channel. Each function is obtained by fitting a quadratic log-linear regression to a set of (q,$PER^{AWGN}_{m,p}$)pairs (q Є {γ, I}) obtained from simulations.

IV.LINK QUALITY METRICS

The first LQMs is based on the concept of MI. The second LQM relies on a weighting of the entries in Γ in a log-sum-exp manner. The MI based LQMs basically compute the mean MI (MMI) per subcarrier symbol in the receiver, where the MI of one symbol is obtained by averaging the MIs of the bits mapped in this symbol [5]. This LQM corresponds to the mean MI between the stream of coded bits {c} at the output of the puncturer in the transmitter and the corresponding stream of LLRs {L(c)} at the output of the de-interleaver in the receiver. The accuracy of the two investigated LQMs is assessed in frequency-selective channels.

A. Mean Mutual Information per Coded Bit Mapping (MMIBM)

MI-based metrics are used in system-level simulations to estimate the PER since they achieve a high PER estimation accuracy for a large variety of realizations of the channel transfer function [6], [11]. In [5], an MI-based LQM is suggested for system-level simulations in IEEE 802.16e. This metric computes the effective MMI per (sub-carrier) symbol

$$\mathrm{I}'_{eff}(m;\Gamma) = \frac{1}{N_{SS}N_{SD}} \sum_{j=1}^{N_{SS}} \sum_{k-1}^{N_{SD}} \mathrm{I}_{M(m)}(\gamma_j[k]) \tag{6}$$

The PER is estimated by inserting I = I'_{eff} (m;Γ) in the corresponding function $\psi_{m,p}(I)$ depicted in Figure 3. The function $I_M(\gamma)$ in (6) is the MI per symbol for the modulation format M at SNR γ. The function M(m) specifies the modulation format of MCS m. For the MaxLog demapper under consideration $I_M(\gamma)$ is selected as follows:

$$\begin{aligned}
&\mathrm{I_M}(\gamma) = J(\sqrt{8\gamma});M = BPSK\\
&\mathrm{I_M}(\gamma) = J(\sqrt{4\gamma});M = QPSK\\
&\mathrm{I_M}(\gamma) \approx \frac{1}{2}J(0.8818\sqrt{\gamma}) + \frac{1}{4}J(1.6764\sqrt{\gamma}) + \frac{1}{4}J(0.9316\sqrt{\gamma});M = 16QAM\\
&\mathrm{I_M}(\gamma) \approx \frac{1}{3}J(1.1233\sqrt{\gamma}) + \frac{1}{3}J(0.4381\sqrt{\gamma}) + \frac{1}{3}J(0.4765\sqrt{\gamma});M = 64QAM
\end{aligned} \tag{7}$$

Assuming an equivalent Gaussian channel for each sub-carrier after MMSE equalization [11], $I_M(\gamma)$ is given in closed form as a function of the SNR γ for M = BPSK and M = QPSK [8]. No closed-form expression for $I_M(\gamma)$ is known for the high-order modulation formats M = 16QAM and M = 64QAM. In [5], $I_{16QAM}(\gamma)$ and $I_{64QAM}(\gamma)$ are approximated by numerical integration of the LLR histogram. These relations are then approximated with the linear combinations of expanded/compressed versions of $J(\gamma)$ given in (7). We propose a simple and more elegant method to derive an approximation of $I_{16QAM}(\gamma)$ and $I_{64QAM}(\gamma)$. The method computes first the MMI using the reliability of the LLRs along [12]:

$$I_{LLR}(L) = \left(\frac{1}{N_{symb} N_{SS} N_{SD} N_{bits}}\right) \cdot \sum_{n=1}^{N_{symb}} \sum_{j=1}^{N_{SS}} \sum_{k=1}^{N_{SD}} \sum_{i=1}^{N_{bits}} f\left(\left|L_j^n[k](c_i)\right|\right) \tag{8}$$

In this expression, N_{symb} is the number of OFDM symbols, N_{bits} is the number of bits mapped to one sub-carrier symbol, $L^n_j[k](c_i)$ is the LLR of the i-th coded bit in the n-th OFDM symbol for sub-carrier k of the j-th spatial stream, and $L = [L^n_j[k](c_i)]_{j=1,\dots,NSS; k=1,\dots,NSD; i=1,\dots,Nbits; n=1,\dots,Nsymb}$. The function $f(\cdot)$ is given by [12]

$$f(x) = \left(\frac{1}{1+\exp(+x)}\right)\log_2\left(\frac{2}{1+\exp(+x)}\right) + \left(\frac{1}{1+\exp(-x)}\right)\log_2\left(\frac{2}{1+\exp(-x)}\right), x \geq 0 \tag{9}$$

Sets of $I_{LLR}(L)$ are computed for 16QAM and 64QAM signaling across the AWGN channel for a wide range of the SNR γ. Then non-linear least-squares fits (cf. [13]) are performed to these sets to obtain the coefficients of the approximations for $I_{16QAM}(\gamma)$ and $I_{64QAM}(\gamma)$ in (7). Notice that the MMI in (8) is not used as an LQM in this paper. It is merely employed to compute the approximations in (7).

The MMI per symbol in (6) is used to estimate the PER of MCSs operating in fading channels [8]. However, simulations show that the MMI per symbol does not accurately estimate the PER in IEEE 802.11n fading channels due to the high dynamic of the MI per symbol (or of the entries in Γ) due to frequency selectivity. As a remedy, in [13] this paper proposes to replace the sum in (6) by a weighted sum of first-order statistics. Inspired by [21], an alternative approach in which the right-hand side of (6) is augmented with a term that reflects this dynamic:

$$I_{eff}(m;\Gamma) = \frac{1}{N_{SS} N_{SD}} \sum_{j=1}^{N_{SS}} \sum_{k=1}^{N_{SD}} I_M(m)(\gamma_j[k]) + \lambda(m)\left[\frac{1}{N_{SS}} \sum_{j=1}^{N_{SS}} \mathrm{var}_k\{I_M(m)(\gamma_j[k])\}\right] \tag{10}$$

The $\mathrm{var}_k\{x\}$ is the sample variance of x computed versus the index k. The motivation for including the correction term is as follows. We know that high frequency selectivity decreases the PER, *i.e.*, leads to a higher I_{eff}. Channel coding across sub-carriers is indeed able to compensate for sub-carriers with low MI per symbol when the frequency transfer function of the channel significantly fluctuates over the ODFM bandwidth. As a result the PER performance is lower than that obtained from the MMI per symbol in (6). The term in the brackets in (10) is used as a measure of the fluctuation of the channel transfer function across the sub-carriers. It is obtained by first computing for each stream the variance of the MIs of the subcarriers and then taking the average of the MI variances of all streams. Note that this approach using I_{eff} in (10) is different from the one proposed in [13] where (6) is replaced by a weighted sum of MI per symbol values. The correction term in (10) considers an estimate of the variance of these values, while in [13] these values are individually weighted.

The parameter $\lambda(m)$ balances the contribution of the MI mean and variance terms in I_{eff}. It is calibrated for each MCS individually by performing a least-squares fit in the log (*PER*) domain [10]:

$$\lambda(\mathrm{m}) = \arg\min_{\lambda}\left\{\sum_{i=1}^{N}\left|e_m^{(i)}(\lambda)\right|^2\right\} \tag{11}$$

Where $e_m^{(i)}(\lambda) = \log\left(\psi_{m,p}\left(q^{(i)}(\lambda)\right)\right) - \log\left(PER_{m,p}^{(i)}\right)$. The parameter N is the number of considered realizations of the channel transfer function, $PER^{(i)}_{m,p}$ is the simulated PER for MCS m, the ith transfer function realization and a given noise variance, while $\psi_{m,p}(q^{(i)}(\lambda))$ is the corresponding estimated PER for the given selection of λ. To calibrate $\lambda(m)$ for a given MCS m it is necessary to consider a sufficiently large number of independent realizations of the channel transfer function [2]. For each MCS m we calibrate λ(m) by considering in total 45-50 realizations of the transfer function of the Channel. The proposed calibration approach is consistent with the method used in [2], [15]. Other PER estimation techniques show similar results [16], [17].

As shown in Figure 4, the introduction of the additional term in (10) with λ(m) selected according to (11) significantly reduces the mean-square error (MSE)

$$\mathrm{MSE}(\mathrm{m}) = \frac{1}{N}\sum_{i=1}^{N}\left|e_m^{(i)}(\lambda)\right|^2 \tag{12}$$

B. Exponential Effective SNR Mapping (EESM)

The second considered metric is the effective SNR proposed in [7] [18]. The metric is defined for a given MCS m to be

$$\gamma'_{eff}(m;\Gamma) = -\beta(m)\log\left(\frac{1}{N_{SS}N_{SD}}\sum_{j=1}^{N_{SS}}\sum_{k=1}^{N_{SD}}\exp\left(-\frac{\gamma_j[k]}{\beta(m)}\right)\right). \tag{13}$$

The parameter β(m) is calibrated with the same method as used to obtain λ(m). The PER is estimated by inserting $\gamma = \gamma'_{eff}(m;\Gamma)$ in the corresponding function $\psi_{m,p}(\gamma)$ depicted in Figure 2.

V. NUMERICAL RESULTS

The PER performances of the single-stream MCSs reported in Table I are depicted in Figure 2 and Figure 3 versus γ and I respectively together with the approximation functions $\psi_{m,pref}$ (γ) and $\psi_{m,pref}$ (I) respectively where a reference packet length p_{ref} = 1024Bytes is considered. The fit provided by $\psi_{m,\ pref}$ (q) to the simulation results is good. Closer inspection of Figure 2 reveals that a single dB change in γ leads to a PER change of up to 1.5 decade. The same comment applies to the PER performance versus I reported in Figure 3. This implies that the LQM function q (m,Γ) must be very accurate. Adaptive the LQM function q (m,Γ) must be very accurate. Adaptive MCS is depicted in fig.4.when the selected MCS does not achieve the target PER feedback is given to transmitter to choose apt MCS. Figure 5 depicts the PER for fast link adaptation based on MMIBM and EESM.

- Each curve indicated in dashed line "fixed MCS" represent the throughput or PER performance versus SNR of one individual MCS m Є Ω.

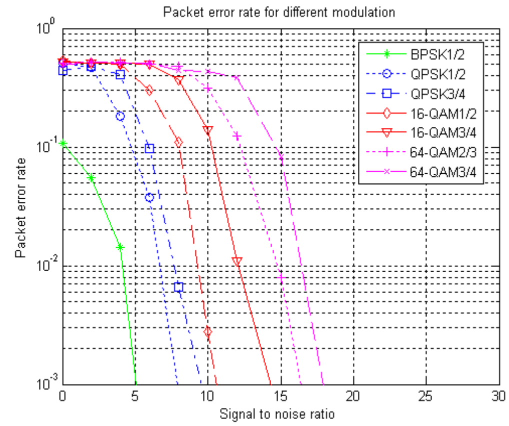

Figure 2. PER vs SNR for various MCS in AWGN channel

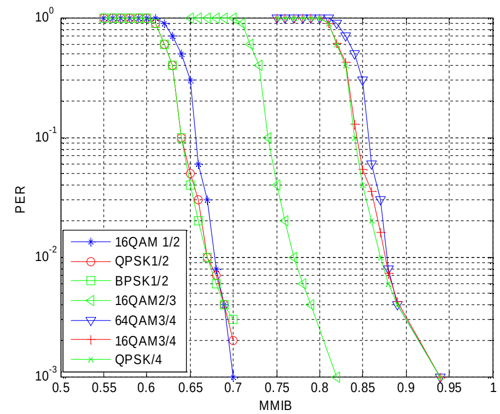

Figure 3. PER vs MMIBM for various MCS

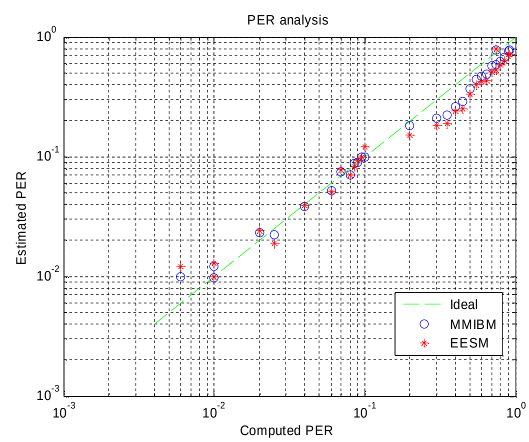

Figure 4. Computed PER vs Estimated PER for 16QAM

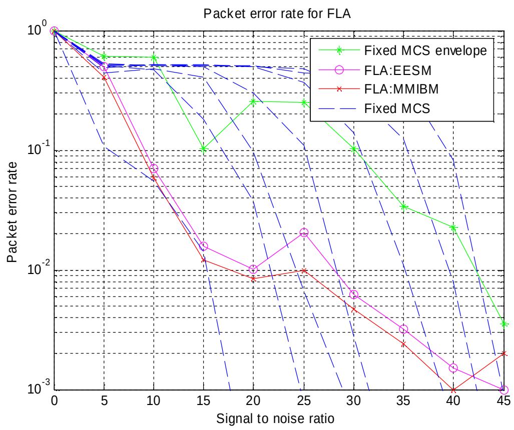

Figure 5. PER vs SNR for FLA

- The reported "fixed MCS envelopes" are obtained for a given SNR by selecting the performance (PER) of the MCS achieving the maximum throughput at that SNR without considering any PER constraints. The bumpiness of the curve results due to the limited number of candidate MCSs, since a smooth transition in performance between the optimum MCSs for two consecutive SNR values is not always realized.
- It is observed that the PER curves of the FLA algorithms using MMIBM, MIESM, are practically lying on top of each other, with a small degradation for EESM around 25 dB SNR.

VI. CONCLUSION

The investigated two link quality metrics (LQMs), *i.e.*, the mean mutual information per coded bit mapping (MMIBM) and the effective SNR mapping (EESM) for the purpose of fast link adaptation (FLA) in a multiple-input, multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) system operating in frequency selective channels. The findings, exemplified for the IEEE 802.11n standard, indicate that the correction parameter for MMIBM considerably improves the accuracy of the packet error rate (PER) estimation. The correction parameter depends on the modulation and coding scheme (MCS); but it is valid for a wide class of channel models. FLA methods using MMIBM slightly outperform EESM in terms of PER. FLA outperforms SLA in channels with low time coherence.

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