

Low complexity link level performance prediction for SIMO systems

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Abstract: In this paper a low-cost link level performance prediction technique is proposed for a single input and multiple output system. Receiver link level abstraction is used in system level simulations of large networks in order to reduce their complexity. Usually, a single lookup table is employed in link level abstraction to predict a receiver's performance under different channel conditions. In the presented work, the mean frame error rate curve of different diverse channels is proposed as the reference for performance prediction in single input multiple output systems. Its generation involves compression of the received code word into a single quality measure based on the postdetection signal to noise ratio values using nonlinear capacity, exponential, and mutual mapping functions. The overall performance difference between simulated and predicted frame error rates shows that the proposed scheme gives very good performance approximations under different modulation and coding schemes, clearly outperforming the classical line of sight channel lookup table.

Key words: Single input and multiple output, mutual information effective SNR mapping, exponential effective SNR mapping, capacity effective SNR mapping

1. Introduction

Current wireless communication systems demand high data rates for which multiple antennas have been proposed at each base station. While many mobile terminals (MTs) have been upgraded to have multiple transmit receive antennas, a substantial number of handheld devices continue to use a single antenna due to their limited form factor. Additionally, the processing complexity at the MT may be intentionally reduced through the use of a single antenna while moving all the signal processing complexity to the base stations. This reduces MT cost while prolonging its battery life. All such single antenna MT devices in current and future networks form a single input multiple output (SIMO) system in the uplink. These SIMO systems are an integral part of any large network and their link level performance abstraction is essential in order to reduce the complexity of the system level simulation.

The link level simulation is used to determine the receiver physical layer performance over a link between communicating entities through complex simulation of all its physical layer functional blocks [1]. A system level simulation involves analyzing the performance of multiple simultaneously communicating entities in a large system. Here an exhaustive physical layer simulation for each independent link is computationally prohibitive. The link level performance abstraction is therefore used as an essential part of the system level simulation in order to predict the receiver performance under different channel conditions at a very low complexity through the use of precalculated lookup tables (LUTs) [2]. The link level performance abstraction involves both training and testing processes. The offline training process is performed only once and is used to generate a lookup

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table. Low complexity real-time testing requires only a single reference curve to accurately predict the behavior under diverse channel conditions and therefore necessitates minimal storage requirements. Only partial link level simulations are performed during real-time operation as most of the link level processing including the high complexity channel decoder, which constitutes the major chunk of receiver complexity, is avoided.

Actual value and average value interfacing methods were proposed in [3] to predict the receiver link level performance for single carrier single input and single output (SISO) systems. However, the results obtained were not good approximations of the simulated values. An improvement over these methods was obtained in [4] through the introduction of linear compression technique for SISO systems. Both scalar and vector compression techniques were explored in [5] and it was established that scalar compression (single dimensional) can provide an acceptable complexity performance tradeoff. Here the postdetection signal to noise ratio (SNR) values were compressed into a scalar signal quality measure, the effective SNR value (SNR_{eff}). Various nonlinear compression techniques were suggested, which penalize the perturbation present in different wireless channels so that the averaging after the transformation provides an accurate measure of the received signal quality. In this regard, exponential, capacity, and mutual information functions were proposed for compression. In [6], a single dimensional compression technique using exponential mapping function was applied to a multicarrier SISO system. In [5,7], single dimensional compression was applied to linear multiple input and multiple output (MIMO) receivers. Here, zero forcing and minimum mean square error filter receivers were investigated using exponential, capacity, and mutual information compression functions. In the literature, LUTs generated using only line of sight/additive white Gaussian noise (AWGN) scenarios have been suggested for MIMO systems [5]. Recently, the link level performance abstraction for SISO using the mean FER curve as a reference was proposed in [8] by the authors of the current paper, which leads to a substantial improvement in the accuracy of the prediction. However, its application and performance in more complex SIMO and MIMO systems are yet to be investigated. Link level abstraction for MIMO iterative receivers were implemented in [9] by estimating the covariance matrix during the transfer of information between the detector and decoder at the receiver. In [10], a precalculated covariance based decoder transfer function was used in order to better predict the signal quality at the output of the decoder in a MIMO iterative receiver.

The generation of appropriate quality measure for SIMO systems, the effect of different compression processes, and the performance prediction using different mapping functions have not been investigated in the literature. All of these issues are, therefore, addressed in this article.

In this paper, an accurate LUT obtained by using the mean FER of different channels is proposed for SIMO system. A link level performance abstraction framework for SIMO systems is implemented by employing single dimensional compression and using mean of the FERs of different channels as a reference curve. The postdetection SNR values have been evaluated for three SIMO diversity combining techniques, i.e. maximum ratio combining (MRC), equal gain combining (EGC), and selection combining (SC) [11]. These SNR values are then compressed into a scalar value by using three nonlinear mapping functions: exponential, capacity, and mutual information functions. The validation results are presented for MRC and SC, which show a very close association between the predicted and link level simulated values. Its comparison with the classical technique using an AWGN channel LUT indicates a substantial improvement in the prediction accuracy where the AWGN LUT directly uses the FER curve for the line of sight channel as a reference.

The remainder of the paper is organized into the following sections. Section 2 explains the system model and the block diagram used for the training and the validation. Section 3 discusses the compression process and the three compression techniques employed for nonlinear effective SNR mapping. Section 4 presents a

discussion on the effect of the shape of the LUT on the accuracy of link level performance prediction. Section 5 discusses the SIMO diversity combining techniques and their postdetection SNR values. Section 6 discusses the validation results. In Section 7, conclusions are drawn.

In the entire article, complex baseband notation is used where scalars are represented by lowercase italics, vectors by lowercase boldface, and matrices by uppercase boldface. The hypothesis, the estimates, and expected value of a quantity such as x are denoted as \tilde{x} , \hat{x} , and $\varepsilon\{x\}$, respectively. The double strike font is used to represent sets, e.g., \mathbb{C} represents the set of complex numbers and \mathbb{X} represents the modulation alphabet set.

2. System model and validation setup

Figure 1 shows a $1 \times N_R$ SIMO system where N_R is the number of receive antennas. A multicarrier OFDM system has been used with IFFT length Q . The q th transmitted symbol x_q is passed through a channel \mathbf{h}_q and the received signal vector \mathbf{y}_q is given as

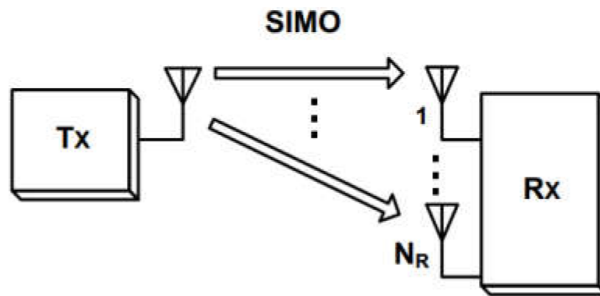


Figure 1. SIMO system block diagram.

$$\mathbf{y}_q = \mathbf{h}_q x_q + \mathbf{n}_q, \tag{1}$$

where $\mathbf{y}_q \in \mathbb{C}^{[N_R \times 1]}$, $\mathbf{h}_q \in \mathbb{C}^{[N_R \times 1]}$, and \mathbf{n}_q is the complex additive Gaussian noise of zero mean and variance σ_n^2 and $x \in \mathbb{X}$, the complex symbol alphabet set with cardinality $|\mathbb{X}| = 2^L$ where L is bits per symbol.

The block diagram in Figure 2 shows the link level performance abstraction training and validation setup for SIMO systems. Source data after encoding, mapping, and modulation are transmitted through a wireless channel. The setup shown at the receiver is used for both training and validation during the link level simulations. The received postdetection SNR values for the q th received symbol (SNR_q) are calculated. These are then used to calculate the scalar value SNR_{eff} at the output of the SIMO receiver through nonlinear compression and mapping.

During the training process the LUTs are generated. The postdetection SNR_q values for the SIMO system are compressed into a single SNR_{eff} value for each frame, which is then mapped against the FER obtained from the link level. A large number of frames are transmitted for each SNR_{eff} value and the histogram obtained is then normalized by the total number of frames passed at each SNR_{eff} value in order to obtain a smooth FER curve. The process is repeated for different channels and for a range of scaling parameters β . Here the scaling parameter β is used to select a reference curve that minimizes the mean square error between FER curves for different channels and is normally calculated offline during the training process. This reference curve is finally stored as a LUT for a specific MCS.

During the validation the link level simulation for the SIMO system is run in parallel with the link level prediction setup to determine the simulated and estimated FER curves at different SNR values. During the link

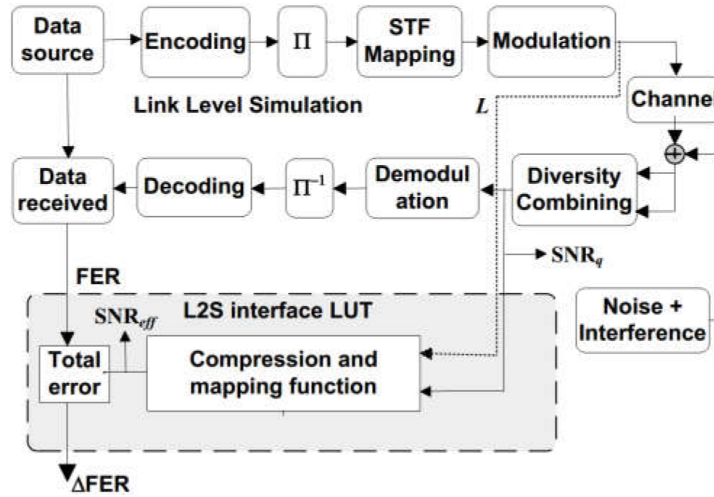


Figure 2. Setup for training (generating lookup-tables) and validation of link level predictions.

level prediction, the SNR_{eff} value for each received codeword is evaluated using a preestimated β_{opt} value. It is then mapped to the link level FER through the LUT.

3. Link level performance abstraction

In the link level performance abstraction two types of compression techniques have been used: single dimensional and two dimensional [5]. In single dimensional compression, a single scalar parameter SNR_{eff} is estimated against which the FERs are plotted to form the LUT. In the two dimensional compression technique, a lookup table is estimated in terms of both mean and variance of the SNR_q values. The resulting lookup table is two dimensional and is computationally very expensive to generate. Besides, the results are only marginally better than those of the single dimensional compression [5]. Consequently, in the present work, only single dimensional compression is considered.

The principle of the single dimensional compression for the link level performance prediction is shown in Figure 3. In wireless communication the data transmitted from the source are subjected to various impairments such as small and large scale fading, path loss, interference, and noise. The received signal is characterized by signal to noise ratio (SNR_q) values at the resource elements spread over the space, time, and frequency domain. These SNR_q values are compressed into a single SNR_{eff} value using nonlinear mapping functions [11] in order to penalize the channels with higher diversity. As a result, the FER values when mapped against the SNR_{eff} values cause the performance curves for different channels to be bunched together and enable us to use a single reference curve for any given receiver. The compression process, therefore, gives us a single parameter, which is an excellent measure of the quality of the received signal. The values are compressed into a single value using nonlinear mapping functions. The compression process is given by [7,12]:

$$SNR_{eff} = \beta \times I^{-1} \left(\frac{1}{Q} \sum_{q=1}^Q I \left(\frac{SNR_q}{\beta} \right) \right), \quad (2)$$

where I is the nonlinear information function used for compression and β is the empirical scaling parameter. The compression process commonly employs nonlinear mapping functions. The three most important ones are described below.

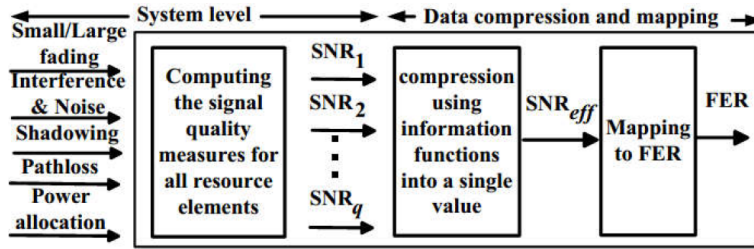


Figure 3. Principle of data compression.

3.1. Mutual information effective SNR mapping algorithm (MIESM)

It is based on the channel capacity function derived by Gallager and is written as [13,14]:

$$I(SNR_q/\beta) = \log_2 L - \varepsilon_Y \left\{ \frac{1}{L} \sum_{l=1}^{\log_2 L} \sum_{b=0}^1 \sum_{z \in X_b^l} g \right\}, \tag{3}$$

$$g = \log_2 \frac{\sum_{\hat{x} \in \mathbb{X}} \exp \left(- \left| Y - \sqrt{\frac{SNR_q}{\beta}} (\hat{x} - z) \right|^2 \right)}{\sum_{\tilde{x} \in \mathbb{X}_b^l} \exp \left(- \left| Y - \sqrt{\frac{SNR_q}{\beta}} (\tilde{x} - z) \right|^2 \right)},$$

where Y is a zero mean unit variance complex Gaussian variable. $\hat{x} \in \mathbb{X}$, where \mathbb{X} is the symbol alphabet set, and $z \in \mathbb{X}_b^l$, where \mathbb{X}_b^l is the set of symbols for which the l th bit equals bit b . ε_Y represents the expected value of Y .

3.2. Capacity effective SNR mapping algorithm (CESM)

It is defined as the Shannon channel capacity formula [15] and is written as:

$$I(SNR_q/\beta) = \log_2 \left(1 + \frac{SNR_q}{\beta} \right) \tag{4}$$

3.3. Exponential effective SNR mapping algorithm (EESM)

The exponential mapping algorithm is defined in terms of the negative exponential function and is written as:

$$I(SNR_q/\beta) = \exp \left(- \frac{SNR_q}{\beta} \right) \tag{5}$$

Most of the existing wireless standards have adopted bit interleaved coded modulation (BICM) [13] and employ convolutional codes (CCs) and turbo codes having high decoding complexities. For example: a CC using the Viterbi decoding algorithm has a complexity of order $O(QL2^M)$ for each codeword and is the primary contributor to the link level processing complexity (here M is the memory of the CC and O is the big- O notation) [16]. The complexity of the turbo encoder using BCJR [17] decoding algorithms is many times higher than that of the Viterbi algorithm. L2S interfacing avoids the channel decoder complexity by direct estimation of the receiver performance using the postdetection SNR values at the receiver without passing it through the decoder [6]. The complexity for SIMO link level performance abstraction is of order $O(QN_R)$, which is much lower than that of a BICM receiver.

4. The effect of LUT shape on the link level performance prediction

The average frame error rate when plotted as the function of the compression parameter (SNR_{eff}) results in LUTs. The LUTs are estimated during the training process for different channels using nonlinear mapping functions. In Figure 4 ideal and empirically determined LUTs for the MCS-1 scheme (see Table 1) using MIESM and EESM compression are shown. The shape of the lookup table is an indicator of the accuracy of the compression parameter in discriminating between the incorrect and correctly estimated frames. Ideally, the LUT table should have a unity value up to a certain critical SNR_{eff} , after which it should immediately drop to zero. This ideal shape of the LUTs indicates that all the frames having SNR_{eff} values larger than this critical value are correctly received while all the other frames are received in error. In all those cases where the estimated LUTs do not have a fast transition from one to zero value, only the average FER can be accurately determined from the LUT and the error event prediction for the individual received frame is subject to error. Figure 4 shows the FER curves as a function of SNR_{eff} values for five different channels using MIESM and EESM compression. Here the slopes of the curves indicate that the LUTs generated using MIESM closely follow the fast transition of the ideal curve and consequently give a better individual frame error prediction. The proposed mean FER of different channels is defined as:

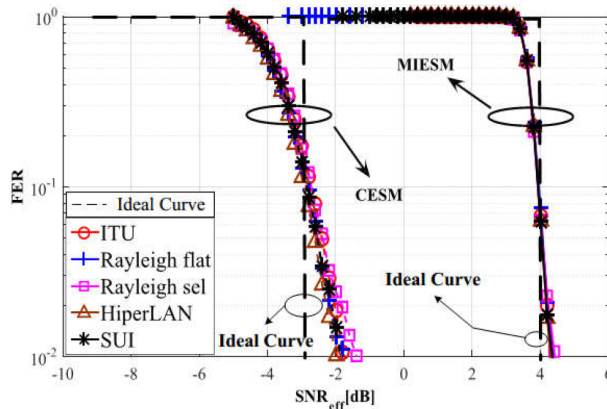


Figure 4. LUTs generated using MIESM for $\beta_{opt} = 1$ and EESM for $\beta_{opt} = 0.8$ with MCS-1.

Table 1. MCSs used for link level system abstraction.

MCS	Modulation	Channel coding, code rate	Bandwidth	No. of carriers
1	4QAM	Turbo, $1/2$	4 MHz	512
2	16QAM	Turbo, $1/2$	4 MHz	512
3	64QAM	Turbo, $1/2$	4 MHz	512

$$FER_{mean,o}(\beta) = \frac{1}{J} \sum_{j=1}^J FER_{j,o}(\beta) \tag{6}$$

where the subscript J represents the total number of channel types considered and o represents the number of SNR_{eff} values used for the calculation. A range of empirical scalar parameters β is normally used along with mapping functions in order to determine the optimal beta value β_{opt} , which will bunch together the

performances of various channels. The mean FER curve at β_{opt} that minimizes the mean square error (MSE) to the FER curves for different channels is adopted as the reference LUT. The β_{opt} is given as [8]:

$$\beta_{opt} = \arg \frac{1}{J|\mathbb{O}_j|} \sum_{j=1}^J \sum_{o \in \mathbb{O}_j} (FER_{j,o}(\beta) - FER_{mean,o}(\beta))^2 \tag{7}$$

where \mathbb{O}_j is the set of SNR simulation points for the j th channel lying in the transition region between the FERs of 0.3 to 0.003 and having cardinality $|\mathbb{O}_j|$ corresponding to the frame error rate. The FER_{mean} curve for β_{opt} is taken as the LUT. In Figure 4, the MIESM FER curves are much closer to each other as compared to the EESM mapping function, indicating a better link level prediction for different channels using a single lookup table. This is also validated by the results shown in Table 2. The variation of MSE with β for the three compression strategies is shown in Figure 5. MIESM has the lowest MSE value of 8×10^{-6} at $\beta_{opt} = 1$. The β_{opt} value for CESM and EESM are 0.9 and 0.8, respectively, at their corresponding lowest MSE values.

Table 2. Validation of various compression functions in L2S interfacing in 1×4 MRC SIMO system using turbo code.

MCS	Compression function	AWGN FER as reference		MEAN FER as reference	
		β_{opt}	MSE (0.003–0.3)	β_{opt}	MSE (0.003–0.3)
1	EESM	1	1.20×10^{-3}	0.8	1.30×10^{-2}
2		1	1.07×10^{-2}	4.6	6.83×10^{-5}
3		1	1.73×10^{-2}	9.4	4.85×10^{-4}
1	CESM	0.7	7.16×10^{-4}	0.9	7.21×10^{-5}
2		0.9	1.60×10^{-3}	0.7	1.45×10^{-4}
3		0.9	4.44×10^{-4}	0.1	2.50×10^{-4}
1	MIESM	1	1.09×10^{-4}	1	1.34×10^{-4}
2		1	1.07×10^{-4}	1.4	1.03×10^{-4}
3		1	3.78×10^{-5}	0.9	4.95×10^{-5}

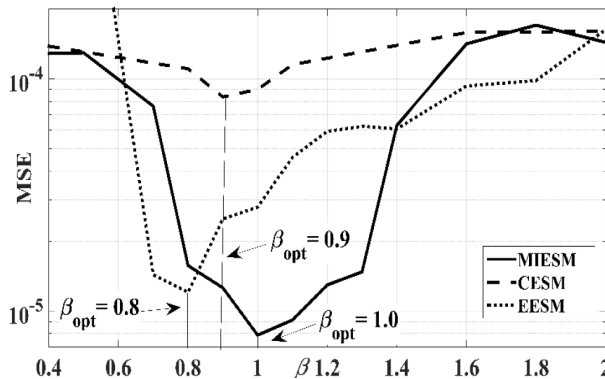


Figure 5. MSE between FER curves of different channels for MCS-1

5. SNR estimation for SIMO systems

Correct SNR estimation is critical for accurate link level performance abstraction. The deteriorating effects of fading and multipath in wireless systems can be compensated through diversity combining techniques in SIMO. The independent fading signals associated with multiple receive antennas are combined to get a more reliable

estimate of the transmitted signal. The most common receiver diversity combining techniques are selection combining (SC) and maximum ratio combining (MRC). The postdetection SNR values for these diversity combining techniques are as follows.

5.1. Selection combining (SC)

In selection combining, the combiner outputs the signal from the receive antenna with the highest SNR value. Since only one output is used, multiple branch co-phasing is not required. The SNR at the q th resource element is given as:

$$SNR_q = \max(SNR_q^1, SNR_q^2, \dots, SNR_q^{N_R}), \quad (8)$$

where the superscripts represent the receive antenna.

5.2. Maximum ratio combining (MRC)

In MRC the output is the weighted sum of the signals received at the N_R receive antennas. In MRC the signal in each branch are co-phased by multiplying it with the conjugate value of the received signal before combining. This ensures that the SNR at the output is maximized. The SNR at the q th resource element within the code word is given as

$$SNR_q = \sum_{i=1}^{N_R} SNR_q^i \quad (9)$$

Equal gain combining (EGC) is another important diversity combining technique in which the received signals are simply added together after co-phasing. It can be considered a variant of MRC with magnitudes of weights at each branch equal to one. Its SNR at the q th resource element is given as:

$$SNR_q = \frac{1}{\sigma_n^2 N_R} |\mathbf{1} \cdot \mathbf{y}|^2, \quad (10)$$

where $\mathbf{1} \in \mathbb{1}^{[1 \times N_R]}$ is a row vector with all elements equal to one. Because of its close connection with MRC, the results shown for MRC can be easily extended to EGC. EGC is therefore not analyzed separately in the subsequent section.

6. Validation results

In this section the link level performance prediction scheme is validated for SIMO systems. The simulation is performed on an OFDM system with FFT length of 512 and a channel bandwidth of 4 MHz. A memory two, $1/2$ rate turbo code is used with different modulation schemes resulting in three MCSs as given in Table 1. Each component of the convolutional encoder within the turbo code is systematic and recursive with a generator polynomial $(7, 5)_8$. The results for 3 MCSs are tested on different channels in order to verify the robustness of the estimates. The channels used are: HiperLAN-f, Stanford University Interim (SUI) 6, International Telecommunication Union (ITU) Vehicular A, a single tap Rayleigh flat, and independent identically distributed (IID) Rayleigh channel. The low diversity Rayleigh flat and high diversity IID Rayleigh channel form the two extremes and act as the limits within which the performance of the remaining channels is expected to reside. Both the line of sight and the mean of the FERs of different channels plotted as a function of SNR_{eff} value at β_{opt} are used as reference curves. The results have been shown for a SIMO system employing MRC.

The validation results in Figures 6–9 plot the link level simulated and predicted FER curves in order to ascertain the accuracy of the estimate. Here the solid curves (labeled as ‘link’) for various channels are estimated through the link level simulation while the dotted curves (labeled as ‘system’) are estimates from the reference LUT. The overall performance of various mapping functions for 1×4 MRC SIMO systems are summarized in Table. 2. Here the mean square error (MSE) is calculated for the simulated and predicted FERs for all five channels during the transitional FER of 0.3 to 3×10^{-3}

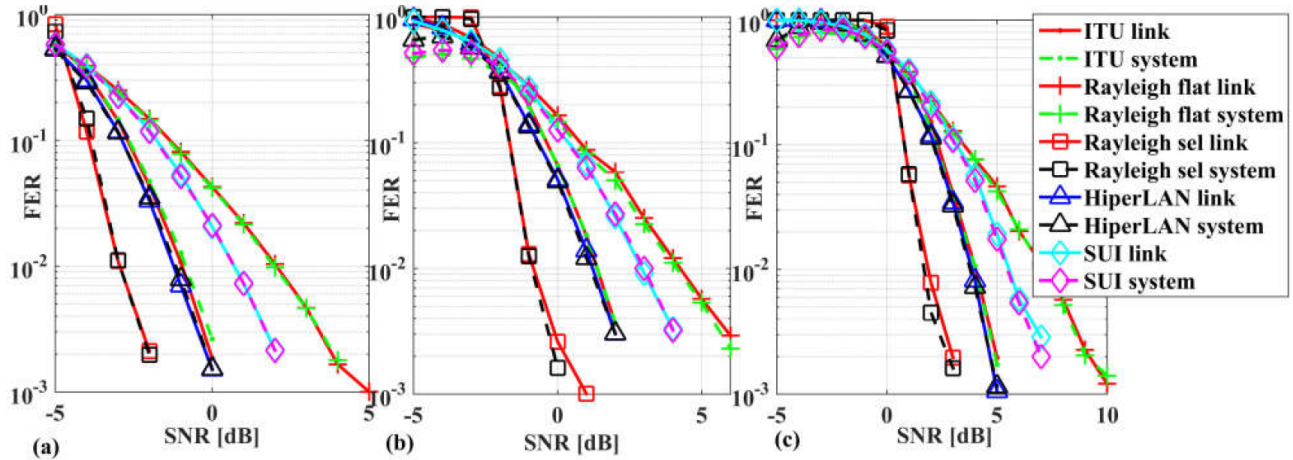


Figure 6. Validation of AWGN LUT generated with MRC using (a) MIESM for $\beta_{opt}=1$ with MCS-1, (b) MIESM for $\beta_{opt}=1.4$ with MCS-2, and (c) MIESM for $\beta_{opt}=0.9$ with MCS-3.

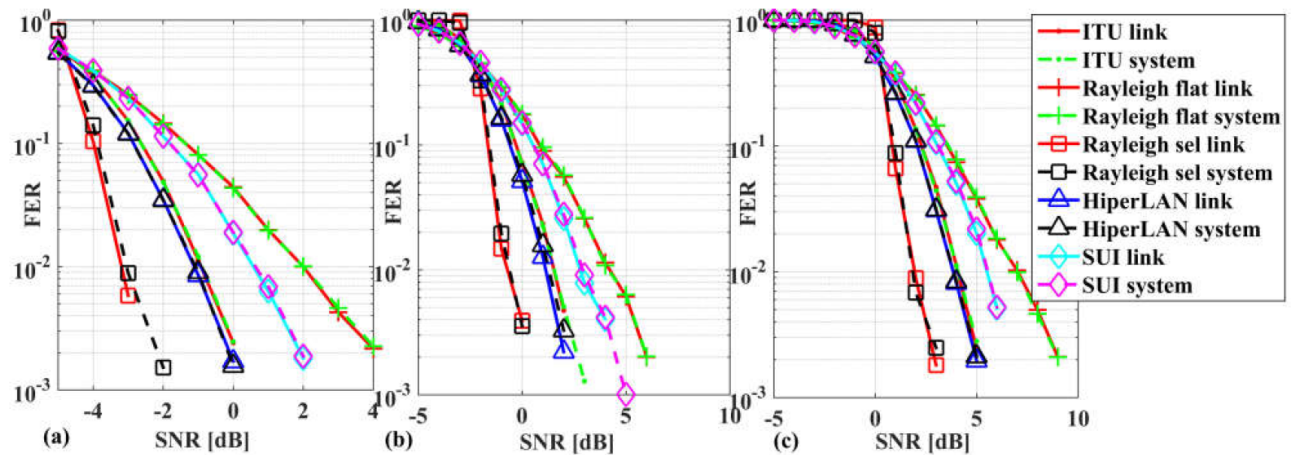


Figure 7. Validation of MEAN LUT generated with MRC using (a) CESM for $\beta_{opt}=0.9$ with MCS-1, (c) EESM for $\beta_{opt}=4.6$ with MCS-2, and (c) MIESM for $\beta_{opt}=0.9$ with MCS-3.

Figure 6 shows the results for the 1×4 MRC SIMO system using the line of sight FER as the LUT for the three MCS schemes. Here the results for only the best of the considered three compression schemes (EESM, MIESM, and CESM) are presented for each MCS. The figures show a close match between the simulated and predicted FER for all three MCS schemes. The performance summary is given in Table 2. While MIESM and CESM results are very good, the prediction accuracy results using EESM compression exhibits a higher MSE value.

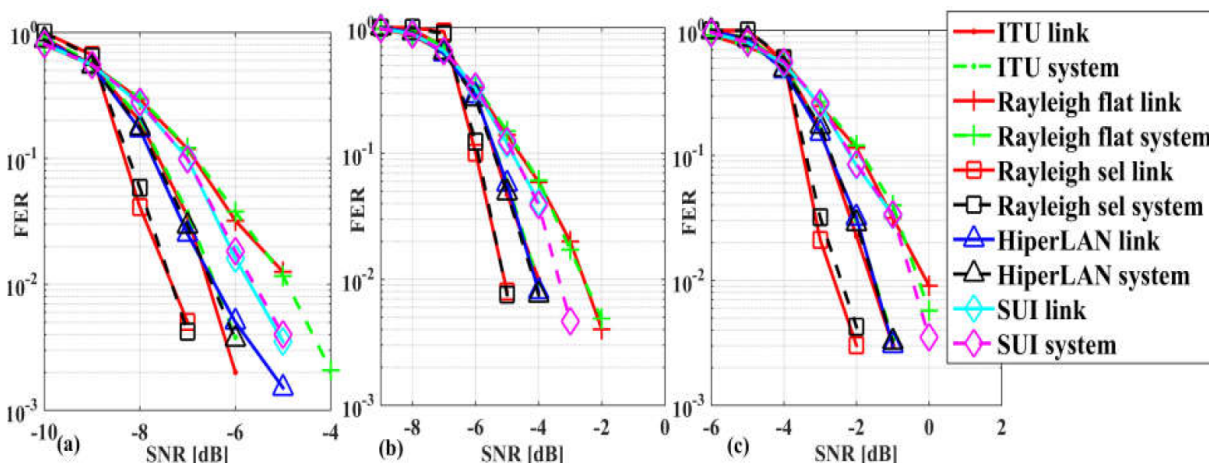


Figure 8. Validation of MEAN LUT generated for 1×10 SIMO system with MRC using (a) MIESM for $\beta_{opt} = 1$ with MCS-1, (b) MIESM for $\beta_{opt} = 1$ with MCS-2, and (c) MIESM for $\beta_{opt} = 1$ with MCS-3.

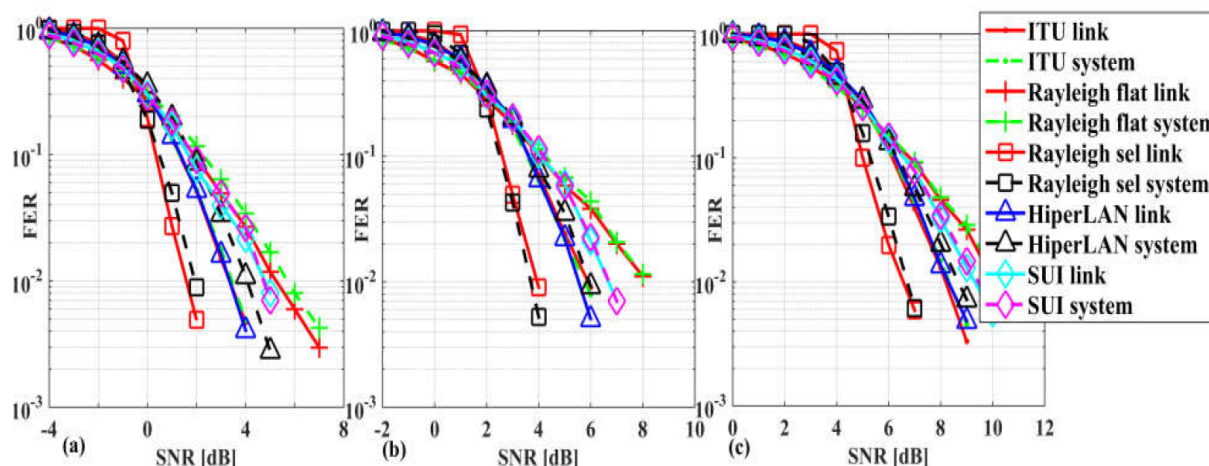


Figure 9. Validation of MEAN LUT generated for 1×4 SIMO system with SC using (a) EESM for $\beta_{opt} = 0.1$ with MCS-1, (b) EESM for $\beta_{opt} = 0.5$ with MCS-2, and (c) EESM for $\beta_{opt} = 1$ with MCS-3.

In Figure 7, results are repeated for the 1×4 MRC SIMO system but now the mean FER curve is used as the LUT. Here again the results for only the best compression scheme for each of the MCSs are presented. The results for MCS-1 and MCS-2 in Figure 7 show a better match between the simulated and predicted value when compared with Figure 6. However, for MCS-3, the results in Figure 6 are marginally better (see Table 2). The MSE values in Table 2 also suggest that the prediction accuracy with mean FER LUT is generally superior to the line of sight LUT for CESM and EESM compressions while the performance is comparable for MIESM.

Figure 8 shows the simulation results for the 1×10 MRC SIMO system using MIESM compression for the three MCS schemes. A very good approximation of the receiver performance under different channels conditions is immediately evident here.

To show that the proposed link layer performance prediction scheme is applicable to other diversity combining schemes, the validation is repeated for the selection combining technique with EESM compression function for the 1×4 SIMO system. The results are shown in Figure 9. The prediction accuracy is again excellent for MCS-2 and MCS-3 and is quite acceptable for MCS-1

7. Conclusion

In this paper an accurate and efficient method for the link level performance abstraction for SIMO systems is proposed. Both the line of sight and the mean FER of different channels are used as reference LUTs. The postdetection SNR value for the SIMO system is used for the link level performance prediction using capacity, exponential, and mutual information compression functions. The optimal LUTs are estimated and validated for five different channels. The results for two diversity combining techniques, MRC and SC, have been provided. The validation results show that, by using a simple LUT with mean FER curve, the link level performances can be accurately estimated for different channels with a very small error and are clearly superior to the classical AWGN LUT for CESM and EESM compressions. However, the prediction performances of the two LUTs are comparable for the MIESM compression, which also gives the best overall performance for different modulation and coding schemes.

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