Technical report on validation of error models for 802.11n.

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Abstract

This technical report is to support a new packet error rate model for OFDM signals that is based on end to end link simulation in MATLAB using reliable WLAN system toolbox for 802.11n/ac SISO and 2x2 MIMO for use in the ns-3 discrete event network simulator wireless models. This error model is validated against accepted TGn proposed results.

1. Introduction

In 2010, YANS error model (for AWGN channel) in ns-3 which is based on analytical bound was replaced with NIST error model however both the error model fails to align with recent link simulator results for 802.11a and 11n [1], [2]. The modification to improve error models are proposed for hard decision decoding in [1] although the existing YANS error model shows close alignment with 802.11a link simulation results for given SNR definition in Equation 1 and soft decision decoding as shown in Figure 1.

$$SNR = \frac{P_{tx}}{BkT} \tag{1}$$

where P_{tx} is the transmitted power, B is modulated (data+pilot) sub carrier bandwidth (for 20 MHz channel 802.11n $B = 20 * \frac{56}{64} MHz$), k is Boltzman constant = 1.3807 x 10^{-23} J/K and T is ambient temperature in deg. Kelvin. while for frequency selective channel, SNR per sub carrier i is given by

$$\gamma_i = \frac{P_{tx}}{N} \frac{|H_i|^2}{\sigma_i^2} \tag{2}$$

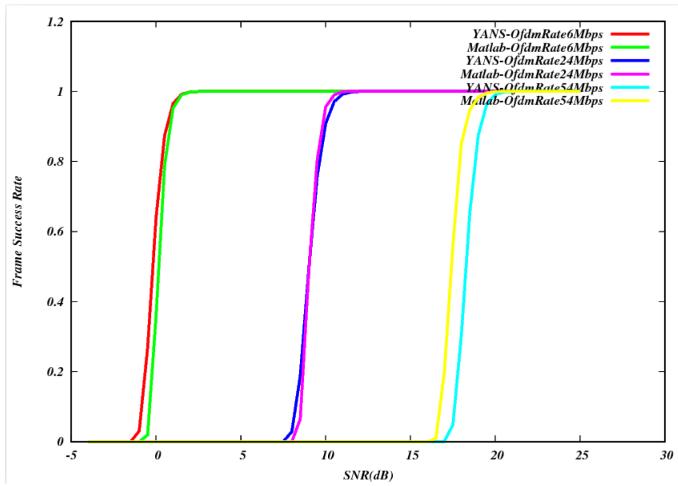


Figure 1: Frame Success Rate vs SNR comparison of YANS error model with MATLAB Link sim for 802.11a soft decision decoding

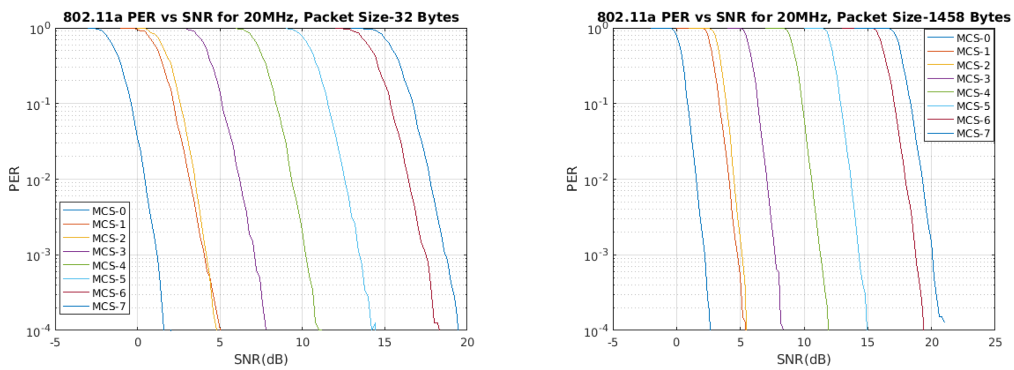
where $\sigma_i^2 = B_{sc} kT$ with $B_{sc} = 312.5$ KHz represents the sub-channel bandwidth in 802.11n and and N is sum total of data and pilot carriers (= 56 for 802.11n).

2. Channel Simulation

To have a look up table for AWGN channel, two reference table for packet size less than 400 bytes and above are considered as per TGax [3] which are 32Bytes and 1458 Bytes respectively, and the corresponding PER vs SNR performance obtained from MATLAB link simulator is shown in Figure 2 for 802.11a and Figure 3 for 802.11n. See Appendix for modulation and coding rates for each MCS for 802.11a/11n/11ac.

Table 1: Profile for TGn channel model D and E

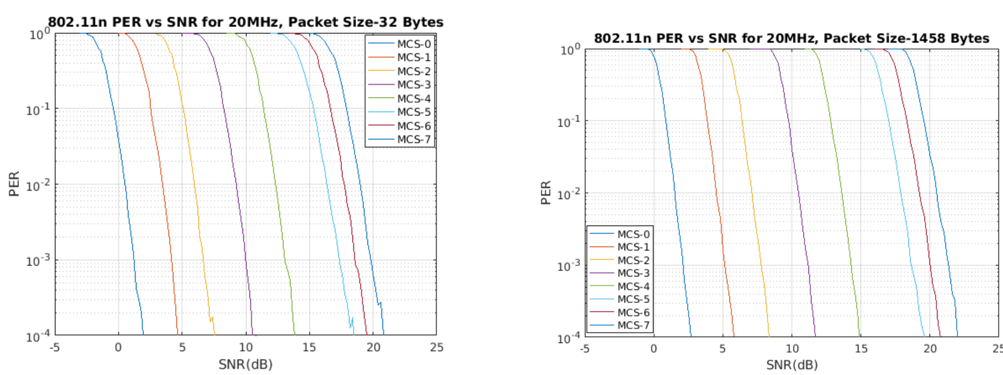
Parameter	Model-D	Model-E
RMS delay (ns)	50	100
Maximum delay (ns)	390	730
Rician K-factor (dB)	3	6
Number of clusters	3	4
Number of taps	18	18
Breakpoint distance(m)	10	20



(a) 32 bytes

(b) 1458 bytes

Figure 2: PER vs SNR for AWGN channel, SISO 32 and 1458 bytes, MCS-0 to 7, 802.11a



(a) 32 bytes

(b) 1458 bytes

Figure 3: PER vs SNR for AWGN channel, SISO 32 and 1458 bytes, MCS-0 to 7, 802.11n

Further to incorporate frequency selectivity, we have considered channel models described in [4] mainly model D and E. The properties of these channels is provides in Table 1.

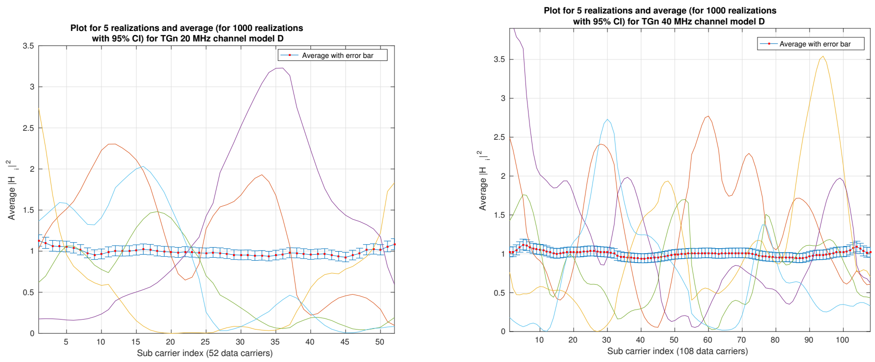


Figure 4: Average $|H_i^2|$ for bandwidth 20 and 40 MHz channel model D

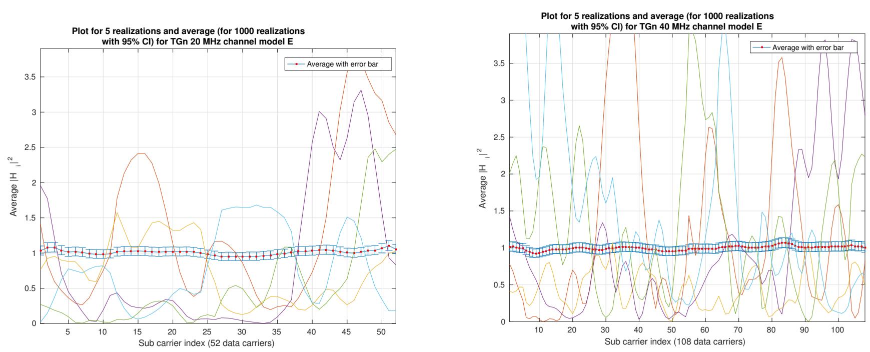
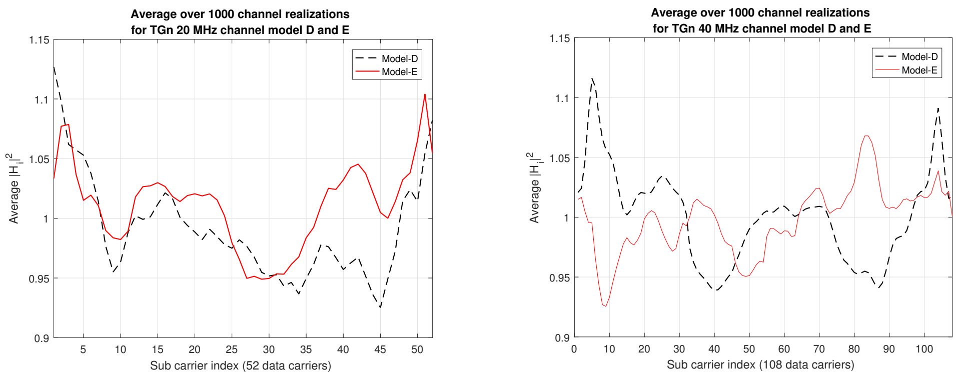


Figure 5: Average $|H_i^2|$ for bandwidth 20 and 40 MHz channel model E

For 20 and 40 MHz channel bandwidth, the channel characteristic $|H_i|^2$ averaged over 1000 realizations and 5 different channel realizations are shown in Figure 4 for channel model D and in Figure 5 for channel model E respectively. In the curve for average $|H_i|^2$ (exponential distributed), error bars for 95 % confidence interval is also shown. These channel characteristics are observed for transmitter-receiver distance of 10m.

Each channel sub carrier is complex normal distribution with each real and imaginary component distributed as $N(0, 0.5)$, hence $|H_i|^2$ should be exponential distributed with parameter $\lambda = 1$ which is shown in Figure 7



(a) 20MHz (b) 40MHz

Figure 6: Average $|H_i^2|$ for bandwidth 20 and 40 MHz channel model E magnified from Figure 4 and

where 1000 points for a subcarrier index i = 28 (picked on random) are shown fit to exponential distribution.

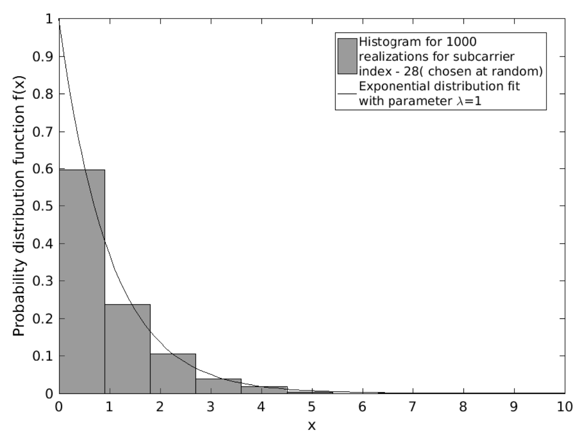


Figure 7: Distribution of a $|H_{28}|^2$

To validate the simulation for frequency selective channels, PER vs SNR curves available in [5] (named as NGWL (Next Generation Wireless LANs) here) for SISO MCS 0 and 7, and model D, E are compared with our simulation in Figure 8 (a) and (b) for 20 MHz.Our curves show better performance than NGWL as we haven't considered any physical layer impairments, following assumptions are considered in setup:

- Ideal channel with perfect estimation of channel is assumed.
- Perfect packet synchronization and packet detection is considered
- No phase tracking and phase correction taken into account
- Noise variance is known at the receiver side.
- Physical layer impairments (Phase noise, carrier frequency offset, non-linearity and others) are not included.

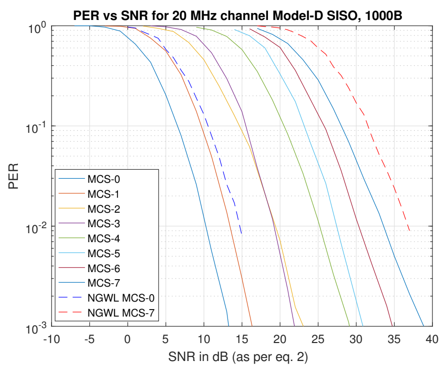
Figure 8 (c) and (d) provides the PER vs SNR performance for 40 MHz channel model D and E.

3. Link to System Mapping: EESM

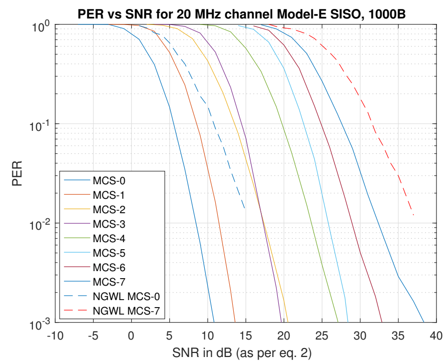
As the name suggests OFDM is frequency domain modulation scheme, it is convenient and suitable to interpret PER performance as a function of the *sub-carrier* SNRs; which unlike AWGN (same for all sub carrier) vary for frequency selective channels. As a result, the PER for frequency selective channels depends, on the SNR for all sub bands. Hence the complexity of such a representation grows linearly with the number of sub-carriers; in the interest of a more efficient representation, the idea of link-to-system mapping via the notion of single *effective* SNR (γ_{eff}) is developed.

One easily implementable method of several for Link-to-system mapping is Exponential Effective SNR Mapping (EESM). EESM is derived based on Union-Chernoff bound on error probabilities [6]. When all the frequency carriers are modulated using same MCS, EESM can be used for SNR mapping. The mapping function is exponential and has jsut one tuning parameter β given by 3:

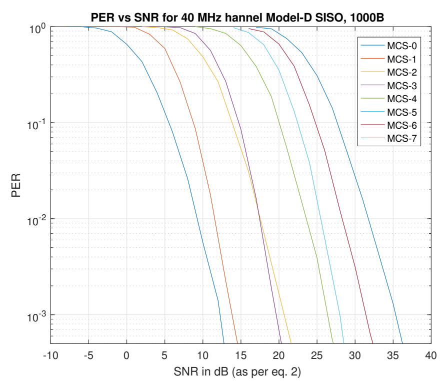
$$\gamma_{eff} = -\beta \ln \left(\frac{1}{N_d} \sum_{i=1}^{N_d} \exp \left(-\frac{\gamma_i}{\beta} \right) \right) \tag{3}$$



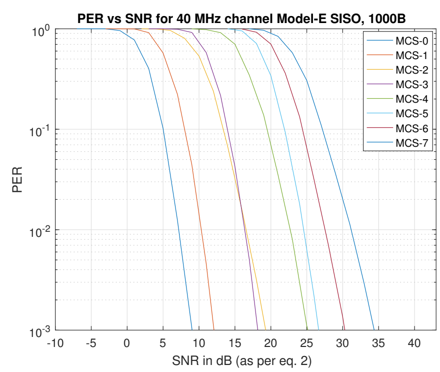
(a) 20MHz, channel-D



(b) 20MHz, channel-E



(c) 40MHz, channel-D



(d) 40MHz, channel-E

Figure 8: PER vs SNR for 20 and 40 MHz channel model-D and E, SISO 1000 bytes

3.0.1. Parameter tuning

Several end to end packet runs are required to tune EESM parameter β for each combination of modulation and coding rate. For each MCS, we performed full link simulation using 400,000 packets for each channel type (TGn Model-D,E etc) with one new channel realization for each packet [1]. For each realization consisting of a single packet, sub-band SNRs γ_i's calculated as per Equation (2) are stored along with decoding result for the packet (0 for correct decoding and 1 for decoding error). The following steps are then carried out to find optimal β

1. Initialize a value of β for EESM and calculate $\gamma_{eff}(\beta)$ for all simulated realizations, as per Equation (3).
2. Combine the collection of $\gamma_{eff}(\beta)$ with corresponding decoding result for all realization. Sort values of $\gamma_{eff}(\beta)$ and quantize into 0.5 dB bins and calculate PER_j for j^{th} bin as per (4).

$$PER_j = \frac{\text{Total packets with decoding error in bin j}}{\text{Total packets in bin j}} \tag{4}$$

   Let $\gamma_{eff,j}$ denote the mean of all γ_{eff} points in j^{th} bin.
3. Corresponding to each bin store PER_j against $\gamma_{eff,j}$ in vectors PER and Γ_{eff} respectively of length L.[2]
4. Interpolate AWGN table (tabulated version of Figure 3) for PER vector calculated in step-2 and store obtained SNR, in vector Γ_{AWGN} of length L.
5. Calculate Mean Squared Error (MSE) for the two SNR vectors:

$$\frac{1}{L}\sum_{i=1}^{L}\left(\Gamma_{AWGN}(i) - \Gamma_{eff}(\beta, i)\right)^2 \tag{5}$$

6. Update β using an iterative optimization method to minimize MSE. We employ Nelder-Mead simplex direct search algorithm to update β. Move to step-3 with updated parameter, repeat for desired number of iterations (we performed 200 iterations).

[1] This effectively corresponds to a fast fading scenario, thus the resultant PER obtained is the *average* PER over all the channel realizations

[2] For PER_j down to 10^{-3}, vector size L is in range [7,9].

In Step 3, the number of packets in a bin should be high enough to ensure small error bar for the PER_j. It is controlled by two parameters: the SNR (in Eq. 1) such that corresponding PER (in Figure 8) lies in range $[1.0, 10^{-2}]$. The other factor is the choice of the number of packets sent per selected SNR.

3.1. Validation Method and Results

The EESM results were validated in accordance to TGax evaluation methodology (see step 3 for Box 0 in [3]). Choose the optimal parameters for choosen channel model for EESM technique validation and have simulated AWGN results tabulated (PER vs SNR) for required packet size PL or interpolate the results using 6:

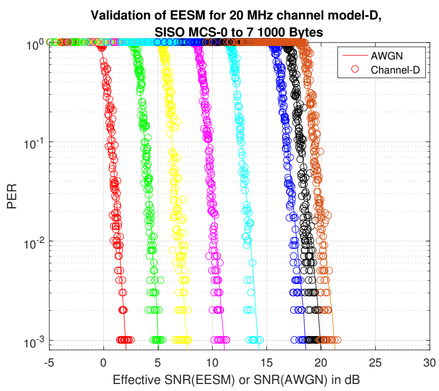
$$PER_{PL} = 1 - (1 - PER_{PL_o})^{PL/PL_o} \tag{6}$$

where PER_{PL_o} is PER table for reference packet size. Further simulate end to end simulation for the selected channel model over a range of SNR in 2 dB spacing in intersecting region as and:

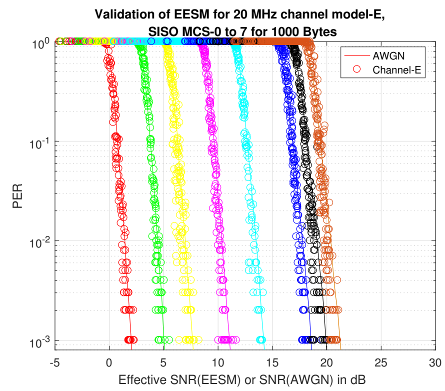
1. For each SNR, simulate over at least 100 independent channel realizations.
2. For each realization run at least 1000 packets and for each packet decide if it has been successfully received using receiving end decoding and record the PER for each realization.
3. For each such realization, find the Effective SNR utilizing the sub carrier SNRs and β value.
4. From the look up table for SNR, find the predicted PER corresponding to effective SNR.
5. Further to evaluate the performance of mapping technique, the predicted and recorded PERs for each channel realization can be compared using MSE metric.
6. For Visual comparison, the recorded PER for each realizations can be scatter plotted over the AWGN curve.

4. SISO Configuration

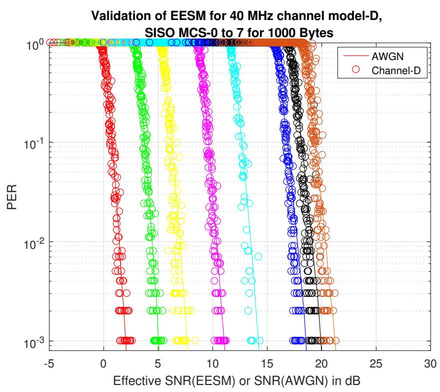
The subcarrier SNR definition under SISO condition remains same as in equation 2. The validation of EESM method using optimal parameters is performed for 20 and 40 MHz bandwidth channel for model D and E for MCS 0-7. Figure 9 presents the level of alignment between AWGN PER



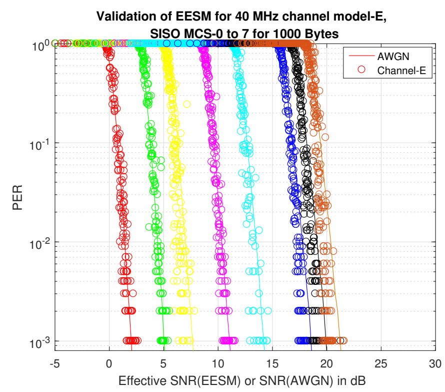
(a) 20MHz, channel-D



(b) 20MHz, channel-E



(c) 40MHz, channel-D



(d) 40MHz, channel-E

Figure 9: EESM Performance for 20 and 40 MHz channel model-D, E, SISO 1000 bytes MCS 0-7

vs SNR curve and that of frequency selective 20 MHz and 40 MHz channel model D, E for MCS-0 to 7 obtained using EESM.

5. MIMO Configuration

The MIMO channel is implemented using transmit and receive correlation matrices as provided in [4]. The diagram in Fig. 10 shows the blocks for MIMO setting available in MATLAB WLAN System Toolbox.

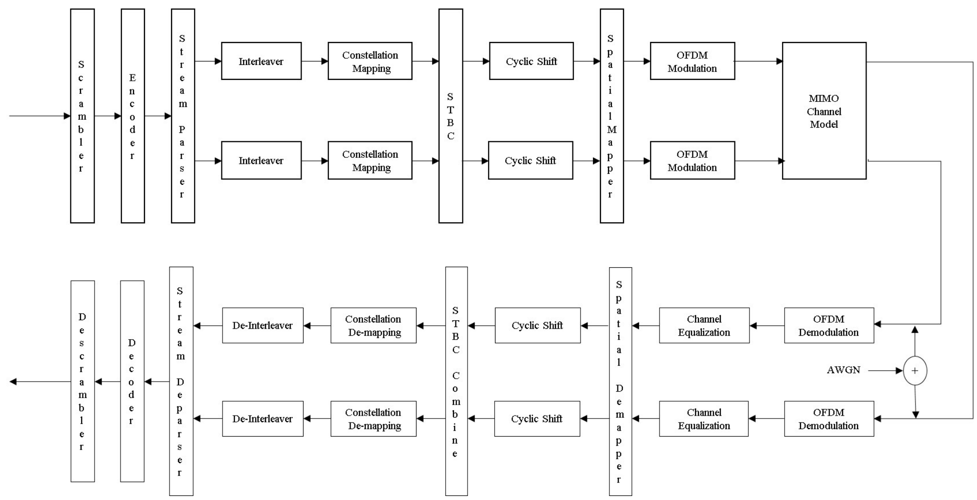


Figure 10: MIMO 2x2 block diagram

The SNR definition in [7] for spatial streams under MIMO 2x2 can be expressed as $\gamma k, i$ for i^{th} spatial stream and k^{th} subcarrier:

$$\gamma_{k,1} = \frac{\sigma^2 H_{1,k}^2 + |det(H_k)|^2}{\sigma^2(\sigma^2 + H_{2,k}^2)} \tag{7}$$

$$\gamma_{k,2} = \frac{\sigma^2 H_{2,k}^2 + |det(H_k)|^2}{\sigma^2(\sigma^2 + H_{1,k}^2)} \tag{8}$$

where $H_k = \begin{bmatrix} h_{11,k} & h_{21,k} \\ h_{12,k} & h_{22,k} \end{bmatrix}$,
$H_{m,k}^2 = \sum_{i=1}^{i=2} |h_{im,k}|^2$ and $h_{ij,k}$ is complex channel parameter (in frequency domain) between i^{th} receiver and j^{th} transmitter for the k^{th} subcarrier.

Further the EESM for multiple spatial stream is defined in equation 9:

$$\gamma_{eff} = -\beta \ln \left(\frac{1}{N_d N_{ss}} \sum_{j=1}^{N_{ss}} \sum_{k=1}^{N_d} \exp\left(-\frac{\gamma_{k,j}}{\beta} \right) \right) \tag{9}$$

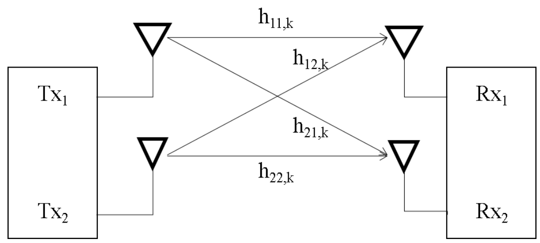


Figure 11: Channel for 2x2 MIMO

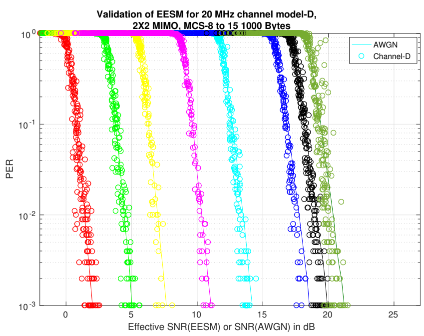
where N_d is the total number of subcarriers and N_{ss} is the number of spatial streams (for 2x2 MIMO, $N_{ss} = 2$).

Following the procedure described in 3.0.1 for parameter tuning, the optimal β values are obtained for MIMO MCS 8 to 15 provided in Table 2 and 3 for 20 and 40 MHz channel respectively.

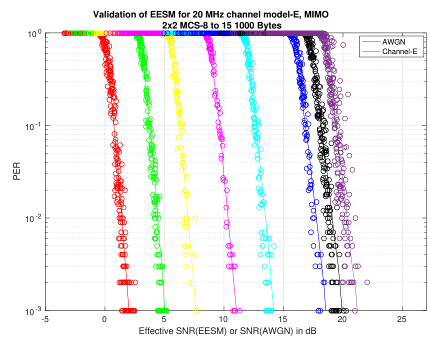
Further validations are performed according to steps in 3.1. The figure 12 presents the level of prediction for MCSs 8 to 15 for MIMO physical layer abstraction. The performance is also tabulated considering MSE between predicted and actual PER in Tables 4 and 5.

Table 2: EESM optimal parameter for MIMO 2x2 channel model-D and E 20MHz

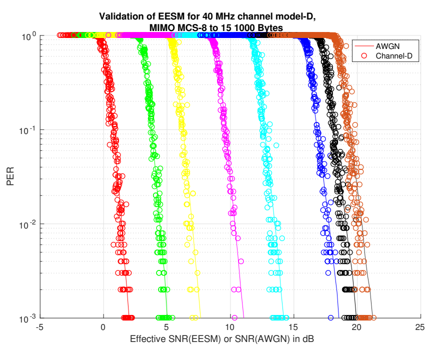
MCS	Channel D 20 MHz		Channel E 20MHz	
	Optimal β	MSE	Optimal β	MSE
8	0.79	0.0014	0.98	0.0038
9	1.65	0.0117	2.02	0.0147
10	1.75	0.013	1.68	0.0082
11	7.56	0.0143	6.90	0.0147
12	8.66	0.0331	7.96	0.0025
13	29.22	0.0375	29.07	0.0640
14	32.93	0.0295	30.91	0.0284
15	34.84	0.0353	33.58	0.0222



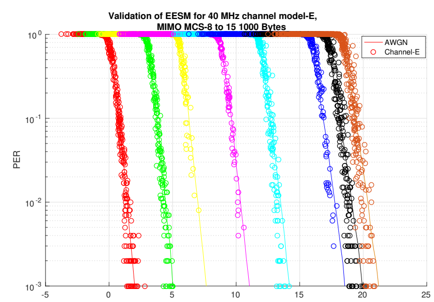
(a) 20MHz, channel-D



(b) 20MHz, channel-E



(c) 40MHz, channel-D



(d) 40MHz, channel-E

Figure 12: EESM Performance for 20 and 40 MHz channel model-D, E, MIMO 2x2 1000 bytes MCS 8-15

Table 3: EESM optimal parameter for MIMO 2x2 channel model-D and E 40MHz

MCS	Channel D 40 MHz		Channel E 40MHz	
	Optimal β	MSE	Optimal β	MSE
8	0.79	0.0006	0.76	0.0014
9	1.74	0.0101	1.58	0.0093
10	1.73	0.0116	1.68	0.0197
11	7.16	0.0118	6.85	0.0179
12	8.67	0.0045	8.50	0.0330
13	31.56	0.0664	28.96	0.0600
14	33.74	0.0494	31.02	0.0316
15	35.51	0.0230	31.56	0.0285

Table 4: EESM performance for channel model-D,E for 20 MHz bandwidth.

MCS Index	MSE	
	Model-D 20 MHz	Model-E 20 MHz
8	0.0354	0.0852
9	0.0251	0.1280
10	0.0479	0.0951
11	0.0090	0.0159
12	0.0630	0.0763
13	0.0650	0.0406
14	0.1248	0.0731
15	0.0168	0.0634

6. Conclusion

In this report, packet error rate performance for 802.11a and 802.11n under AWGN channels and frequency selective channels are presented. Moreover EESM based effective SNR mapping technique is described and implemented for SISO and 2x2 MIMO configuration and IEEE TGn defined frequency selective channels. The PER vs SNR mapping results for frequency selective channels shows close concurrence with AWGN results which makes EESM acceptable for abstraction in system level simulation to improve time efficiency. However there remains consideration of interference, and decreasing performance for higher MCS rates, a challenge to be considered.

Table 5: EESM performance for channel model-D,E for 40 MHz bandwidth.

MCS Index	MSE	
	Model-D 40 MHz	Model-E 40 MHz
8	0.0250	0.0827
9	0.0055	0.0206
10	0.0316	0.0539
11	0.0298	0.0649
12	0.0383	0.1723
13	0.1474	0.0703
14	0.1082	0.1272
15	0.0931	0.2313

References

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Table .6: MCS Table for 802.11a

MCS Index	Modulation	Coding	Rate
0	BPSK	1/2	6
1	BPSK	3/4	9
2	QPSK	1/2	12
3	QPSK	3/4	18
4	16-QAM	1/2	24
5	16-QAM	3/4	36
6	64-QAM	2/3	48
7	64-QAM	3/4	54

Table .7: MCS Table for 802.11n and 11ac

HT MCS	VHT MCS	Spatial Streams	Modulation	Coding	20 MHz Data Rate	40 MHz Data Rate
0	0	1	BPSK	1/2	6.5	13.5
1	1	1	QPSK	1/2	13	27
2	2	1	QPSK	3/4	19.5	40.5
3	3	1	16-QAM	1/2	26	54
4	4	1	16-QAM	3/4	39	81
5	5	1	64-QAM	2/3	52	108
6	6	1	64-QAM	3/4	58.5	121.5
7	7	1	64-QAM	5/6	65	135
-	8	1	256-QAM	3/4	78	162
-	9	1	256-QAM	5/6	n/a	180
8	0	2	BPSK	1/2	13	27
9	1	2	QPSK	1/2	26	54
10	2	2	QPSK	3/4	39	81
11	3	2	16-QAM	1/2	52	108
12	4	2	16-QAM	3/4	78	162
13	5	2	64-QAM	2/3	104	216
14	6	2	64-QAM	3/4	117	243
15	7	2	64-QAM	5/6	130	270
-	8	2	256-QAM	3/4	156	324
-	9	2	256-QAM	5/6	n/a	360