Efficient Link-to-System Mappings for MU-MIMO Channel D Scenarios in 802.11ac WLANs

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ABSTRACT

Results are presented from an extensive campaign of link simulations for multi-user multi-input multi-output (MU-MIMO) scenarios of 802.11ac wireless local area networks (WLAN) for use within a link-to-system mapping framework for ns-3 network simulation. As in [2], Exponential Effective SNR Mapping (EESM) is used inclusive of the impact of channel estimation, but this works extends beyond SISO to MU-MIMO. MATLAB® link simulation results using the WLAN Toolbox™ are used to generate an error rate table lookup for EESM to produce a corresponding packet error rate (PER) for use by ns-3. The simulation programs are made available to allow reproduction and extending of the baseline results.

CCS CONCEPTS

• **Networks** → Network simulations; •**Computing methodologies** → Discrete-event simulation;

KEYWORDS

Multi-user multi-input multi-output (MU-MIMO), Exponential effective SINR mapping (EESM)

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1 INTRODUCTION

802.11ac (ratified in 2013) or WiFi 5 is the current WLAN standard that built on the predecessor 802.11n MIMO WLAN to achieve Gbit data rates by pushing on three dimensions: greater channel bandwidth, more MIMO spatial streams, and higher modulation order [1]. The roll-out of 802.11ac was divided into 2 phases: Wave 1 and Wave 2, with the latter introducing downlink multiuser MIMO (MU-MIMO) capable of further increasing the aggregate network capacity by serving multiple users simultaneously over the same time-frequency resource. Simulation of an 802.11ac network requires an accurate link error probability model that can be used by a link-to-system mapping method such as exponential effective SNR mapping (EESM) to yield an equivalent packet error rate (PER) required for network simulation [2]. This method is equally applicable to 802.11ax (WiFi 6) MU-MIMO scenarios.

2 MU-MIMO CONFIGURATION

Consider a MU-MIMO downlink (DL) channel with a single access point (AP) equipped with N_t transmit antennas and N_u downlink users with $N_{\text{ss},i}$ spatial streams for the *i*-th station (STA). The number of receive antennas per STA is assumed to equal the number of spatial streams. For N_u = 1 (conventional downlink single-user MIMO) we have

$$Y_i = X_i W_i H_i \tag{1a}$$

where Y_i is the received downlink signal at user i, X_i is the transmitted data to user *i* (dimension $1\times N_{ss,i}$ representing the number of spatial streams for user *i*), H_i is the channel matrix between the transmitter and user *i* (dimension $N_{\text{TX}}\times N_{RX,i}$) and W_i is the pre-coder matrix for user i (dimension $N_{ss,i}\times N_{\text{TX}}$). For the DL MU-MIMO scenario, the concatenated received signal row vector $\mathbf{Y}$ given by [3]

$$\mathbf{Y}=\mathbf{XWH} \tag{1b}$$

where $\mathbf{X}$ is the transmitted data (row vector of dim N_{Tx}). The symbols at the transmitter antenna output are $\mathbf{XW}$, where $\mathbf{W}$ is square precoding matrix with dimension N_{TX} (number of transmit antennas)$\times \sum_{j=1}^{N_u} N_{ss,j}$ (total number of spatial streams over all the users). Equation (1b) can be re-written in terms of its components as Equation (2)

$$[Y_{N_{\mathrm{RX},1}}\ Y_{N_{\mathrm{RX},2}} \cdots Y_{N_{\mathrm{RX},N_u}}] = [X_{N_{ss,1}}\ X_{N_{ss,2}} \cdots X_{N_{ss,N_u}}] \begin{bmatrix} W_{N_{ss,1}\times N_{\mathrm{TX}}} \\ W_{N_{ss,2}\times N_{\mathrm{TX}}} \\ \vdots \\ W_{N_{ss,N_u}\times N_{\mathrm{TX}}} \end{bmatrix} \left[H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},1}}\ H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},2}} \cdots H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},N_u}} \right] \quad (2)$$

$$SINR_{N_{ss,i}} = \frac{|x_{N_{ss,i}}|^2 |w_{N_{ss,i}\times N_{\mathrm{TX}}} H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},i}}|^2}{\sigma^2 + |x_{N_{ss,1}}|^2 |w_{N_{ss,1}\times N_{\mathrm{TX}}} H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},i}}|^2 + \cdots + |x_{N_{ss,N_u}}|^2 |w_{N_{ss,N_u}\times N_{\mathrm{TX}}} H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},N_u}}|^2 + |X_{N_{ss,1}}|^2 |W_{N_{ss,1}\times N_{\mathrm{TX}}} H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},N_u}}|^2 + \cdots + |X_{N_{ss,N_u}}|^2 |W_{N_{ss,N_u}\times N_{\mathrm{TX}}} H_{N_{\mathrm{TX}}\times N_{\mathrm{RX},N_u}}|^2} \quad (5)$$

2.1 Channel Inversion (CI) MMSE Precoding

Channel inversion (CI) precoding can cancel both the interference generated by multiple spatial streams for the same user (i.e. *intra*-user interference) and interference due to different users (i.e., MU MIMO or *inter*-user interference) that yields MU MIMO channels with large variation among the eigenvalues of the channel matrix. At the transmitter, the Minimum Mean Squared Error (MMSE) precoding matrix for transmission [3] is computed by 'regularizing the inverse':

$$\mathbf{W}_{\mathrm{mmse}} = (\mathbf{H}^{\mathrm{H}}\mathbf{H} + \frac{\mathrm{N_{TX}}}{\rho}\mathrm{I})^{-1}\mathbf{H}^{\mathrm{H}} \quad (3)$$

where $\mathrm{N_{TX}}$ is the number of transmit antennas and ρ is the SNR of the received signal.

2.2 Signal to Interference Plus Noise Ratio (SINR) for MU-MIMO

The Signal to Interference plus Noise Ratio (SINR) [4] for MU-MIMO is defined as:

$$SINR = \frac{P}{I+N} \quad (4)$$

where P is the power of the signal of interest, I is the aggregate interference power of the signals not-of-interest, and N is the noise power. Hence, the SINR per spatial stream is expressed as Equation (5), where σ^2 is the noise variance, and $W_{N_{ss,i}\times N_{\mathrm{TX}}} = [w_{1\times N_{\mathrm{TX}}} \cdots w_{N_{ss,i}\times N_{\mathrm{TX}}}]$, $X_{N_{ss,i}} = [x_1 \cdots x_{N_{ss,i}}]$.

2.3 Simulation Setup

The link-to-system mapping abstracts a MU-MIMO link with a fading channel between the AP and each user. To create this mapping, two simulations are required: 1) a MU-MIMO simulation with fading channel which determines the PER vs. SNR for MCS combinations and 2) a SISO AWGN simulation which determines the PER vs. SINR for MCS combinations. Both simulations follow CC-59 [5] assumptions:

i. Perfect channel state (CSI).
ii. Perfect packet synchronization and header detection.
iii. No phase tracking and phase correction.
iv. Noise variance known at the receiver.
v. Physical layer impairments (Phase noise, carrier frequency offset, non-linearity and others) are not included.

Figure 1 shows the implementation of 802.11ac using the WLAN Toolbox™ for MATLAB® [6] that is used for the simulations. The number of packets needed to reliably obtain a PER for a given SNR is computed to ensure that the relative estimation error to the true value should be within 10% (one decimal place) with probability 0.95. Simulations were run till either a minimum value of 400 unsuccessfully decoded packets were observed or a total of 40,000 packets simulated for 6 SNRs per Modulation and Coding Scheme (MCS) was reached.

3 LINK-TO-SYSTEM MAPPING

While multiple link-to-system mapping methods have been proposed, different approaches are better suited (after appropriate tuning) to specific scenarios. For example, EESM is shown to perform better than Received Bit Information Rate (RBIR) for a MU-MIMO 2x(1+1) configuration, while EESM and RBIR are shown to achieve similar accuracy for a wide range of SISO cases [4]. Since EESM has one parameter and is easy to implement in comparison to RBIR (with two parameters and a more complex mapping function), EESM is selected for the implementation.

Assuming all the frequency carriers are modulated using the same MCS, the EESM mapping function yields the effective SINR with only one parameter β as follows:

$$\gamma_{eff} = -\beta \ln(\frac{1}{N_d}\sum_{i=1}^{N_d}\exp(-\frac{\gamma_i}{\beta})) \quad (6)$$

where γ_i is the *i*-th subcarrier SINR, and N_d is the number of subcarriers.

To develop the link-to-system mapping, a set of SINR values per subcarrier and spatial-stream and corresponding packet transmission success are created by simulating a 2x(1+1) MU-MIMO scenario for a large number of channel realizations at different SINRs. The following steps are then carried out to find optimal β.

(1) Pick initial value of β and calculate $\gamma_{eff}(\beta)$ for all simulated realizations, as per Equation (6).

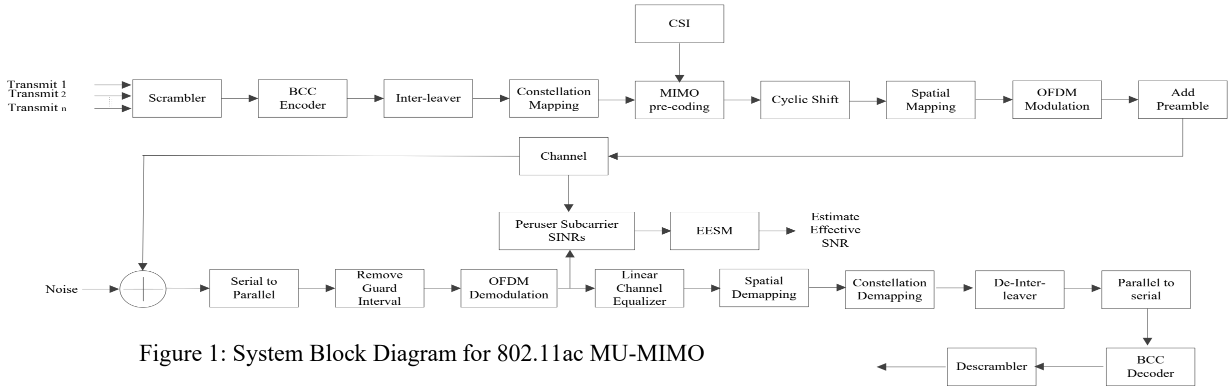


Figure 1: System Block Diagram for 802.11ac MU-MIMO

(2) Combine store $\gamma_{eff}(\beta)$ with corresponding decoding result for all realizations. Sort values of $\gamma_{eff}(\beta)$ and calculate PER_j for *j*-th bin as per Equation (7).

$$PER_j = \frac{\text{Total packets with decoding error in bin } j}{\text{Total packets in bin } j} \tag{7}$$

Let $\gamma_{eff,j}$ denote the mean of all γ_{eff} points in the j^{th} bin.

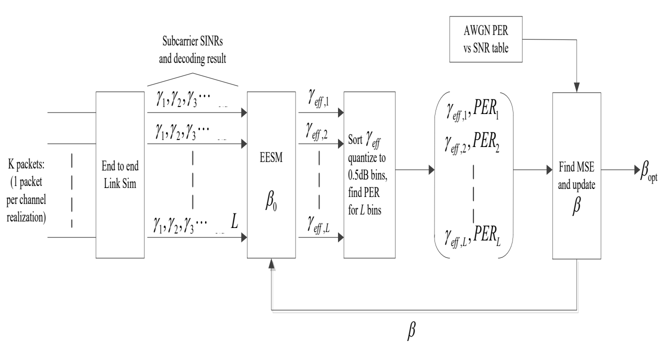
(3) Corresponding to each bin, store PER_j and $\gamma_{eff,j}$ in vectors *PER* and Γ_{eff} .

(4) Interpolate the AWGN table, created as per Section 2.3, for the *PER* vector calculated in Step 2 and store obtained SINR in a vector Γ_{AWGN} .

(5) Calculate the Mean Squared Error (MSE) for *L* bins of the two SINR vectors:

$$\frac{1}{L}\sum_{i=1}^{L}(\Gamma_{AWGN}(i) - \Gamma_{eff}(\beta,i))^2 \tag{8}$$

(6) Update β using an iterative optimization method, such as the Nelder-Mead simplex direct search algorithm, to minimize MSE. Return to Step 1 with updated parameter and repeat for a desired number of iterations.



The diagram in Figure 2 summarizes the above method.

Figure 2: EESM Parameter (β) Tuning Block Diagram

4 SIMULATION RESULTS & CONCLUSION

The described EESM method is utilized for multipath fading channel model D recommended by IEEE TGn [5], for 20 MHz, 2x2 SU-MIMO, and 2x(1+1) MU-MIMO configuration for a packet size of 1000 bytes. The indoor TGn channel has 18 taps for RMS delay spread of 50 ns and the simulation is configured for 10 m transmitter-receiver distance for non-line-of-sight and no large-scale fading. The number of subcarriers N_d in [5] is 56 for 20 MHz inclusive of both data and pilot carriers. Figures 3 and 4 present the results for MCS 0-8 in the case of MU-MIMO and SU-MIMO with optimal β values tabulated in Tables 1 and 2 along with corresponding MSE. The link-to-system EESM mapping MATLAB code for reproducing results is publicly available [7].

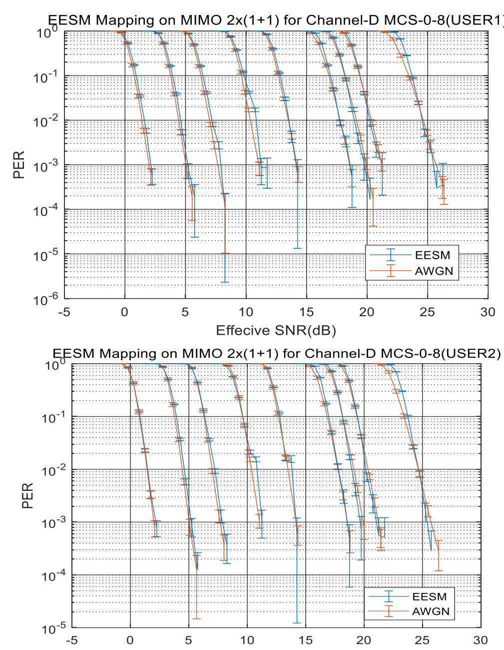


Figure 3: EESM Validation for 20 MHz 2x(1+1) MU-MIMO Channel Model-D

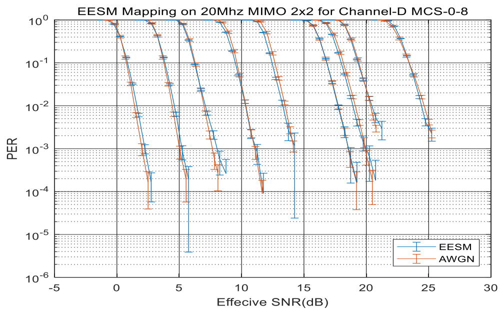


Figure 4: EESM Validation for 20 MHz 2x2 SU-MIMO Channel Model-D

Table 1: EESM Optimal Parameter for 2x(1+1) MU-MIMO Channel Model-D 20 MHz

MCS	Channel D 20 MHz(USER1)		Channel D 20 MHz(USER2)	
	Optimal β	MSE	Optimal β	MSE
0	0.7787	0.0189	0.7256	0.0071
1	1.3168	0.0234	1.3164	0.0203
2	1.4846	0.0381	1.438	0.0272
3	6.3891	0.1197	5.0031	0.0607
4	8.5326	0.0108	8.3417	0.031
5	29.9614	0.0355	30.394	0.0374
6	31.6238	0.0325	31.4207	0.0339
7	34.305	0.0128	33.9595	0.0267
8	132.0668	0.19	134.7699	0.2335
9	NA	NA	NA	NA

Table 2: EESM Optimal Parameter for 2x2 SU-MIMO Channel Model-D 20 MHz

MCS	Channel D 20 MHz	
	Optimal β	MSE
0	0.9871	0.0272
1	1.9559	0.0251
2	1.6748	0.0838
3	8.0840	0.0293
4	8.0219	0.0656
5	32.4371	0.0080
6	30.1389	0.0340
7	31.6879	0.0653
8	112.2006	0.0248
9	NA	NA

EESM results were validated according to the TGax evaluation methodology (see Step 3 for Box 0 in [8]). Figures 3 and 4 show the close correspondence between actual PER observed in the link simulator (the discrete points) and the predicted PER calculated using EESM and effective SINR for the same realization (the solid curve labeled AWGN). The PER results for a specific channel realization can be obtained by selecting β and per-subcarrier γ_i for that channel realization, calculating γ_{eff}, and then selecting PER from the AWGN lookup table given γ_{eff}. From the simulation results in Figures 3 and 4, the PER for each MU-MIMO user is the same as a 2x2 SU-MIMO scenario, i.e., the Channel Inversion precoding algorithm effectively cancels the inter-stream interference generated by multiple spatial streams for the same user.

Finally, the simulation run times for Link-to-System Mappings for 2x(1+1) MU-MIMO and 2x2 SU-MIMO are shown in Table 3 for comparison, for 20 MHz and MCS 0 through 8. The simulations were performed in MATLAB® using 'parfor' with 6 workers. Each curve involved calculating the PER for 12 SNR values and a total of 40,000 packets were simulated for each SNR.

As revealed by Table 3, the results clearly suggest escalating run-times for MU-MIMO at lower MCS, with a full run requiring 10-20 hours. A lower MCS creates a longer packet duration (more symbols per-packet) and the run-time for MCS 0 is almost twice that for MCS 1, with BPSK and QPSK modulation respectively with the same coding rate. The 2x(1+1) MU-MIMO run times are at least twice that of 2x2 SU-MIMO because of the need for running separate per-user optimizations.

Table 3: Run Times (sec) for Link-to-System Mapping for 2x2 SU-MIMO and 2x(1+1) MU-MIMO Channel Model-D 20 MHz

MCS	Channel D 20 MHz	
	SU-MIMO	MU-MIMO
0	17330	77281
1	11100	37336
2	8952	26625
3	7702	22764
4	6730	18207
5	6306	15152
6	6131	14361
7	5987	13593
8	5950	13318
9	NA	NA

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