

Performance Evaluation for Multi-User MIMO IEEE 802.11ac Wireless LAN System

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Abstract—In this paper, we evaluate the performance of the next generation standard IEEE 802.11ac wireless local area network (WLAN) system. IEEE 802.11 for the first time will employ downlink multi-user multi-input multi-output (MU-MIMO) technology. Precoding techniques greatly influences the performance of MU-MIMO transmission. We measure these improvements when realistic channel conditions are applied. We compare the performance of channel inversion (CI) and block diagonalization (BD) precoding methods paired with various MIMO detection techniques. From the simulation results, we show the effectiveness of BD precoding compared to CI precoding.

Index Terms—IEEE 802.11ac system, multi-user MIMO, Linear precoding, MIMO detection, OFDM

I. INTRODUCTION

The next generation standard of 802.11 very high throughput (VHT) wireless local area network (WLAN) systems is currently on development [1]. This new standard, which will be called 802.11ac, promises to provide over 500 Mbps of single station throughput- a five-fold increase compared to the previous 802.11n standard [2]. The recently ratified 802.11n standard uses both orthogonal frequency division multiplexing (OFDM) and multiple input multiple output (MIMO) technologies to provide higher throughput compared to the older 802.11a standard.

This time, 802.11ac for the first time will also employ downlink multi-user MIMO (MU-MIMO) technology that is capable of further increasing the total capacity when a single access point shares the wireless channel between a number of stations. With MU-MIMO, 802.11ac promises to deliver more than 1Gbps of multi-station throughput for use with the ever increasing demand of wireless connectivity. MU-MIMO allows simultaneous transmission from one access point (AP) to multiple stations (STA) in contrast to the time sharing nature of carrier sense multiple access (CSMA) currently used in legacy 802.11n systems. This simultaneous transmission however can only be effectively done when the downlink channel state information (CSI) is available to the transmitter prior to transmission.

Precoding techniques greatly influence the performance of MU-MIMO transmission. In this regard, there are two major classes of precoding namely, non-linear precoding and linear precoding. Non-linear precoding techniques are known to be capacity achieving for obtaining the maximum throughput possible [3], [4]. Some of these non-linear precoding techniques

are Tomlinson-Harashima precoding (THP), Vector Perturbation (VP) and Lattice Reduction Aided (LRA) methods [3], [5]–[8]. However, these techniques have a very high level of complexity and are not supported by 802.11ac. Linear precoding techniques on the other hand are low-complexity transmission techniques and are supported by 802.11ac. Some of these linear precoding techniques are channel inversion (CI) and block diagonalization (BD) methods [3], [4], [9], [10].

Additionally, at the receiver side, the independent signals will need to be separated by using a technique called MIMO detection. Traditional MIMO detection methods include the well known linear MMSE as well as the vertical-Bell laboratories layered space-time (V-BLAST) and LRA decoders [11]–[13]. V-BLAST and LRA techniques improve the performance of the simple MMSE-MIMO decoder. Another high performance MIMO detection algorithm is called the maximum likelihood detection (MLD) algorithm. MLD algorithm has a very high level of complexity and hence impractical. In this paper, we simulated some of these detection algorithms including linear MMSE, V-BLAST MMSE, and LRA MMSE decoders [11]–[13].

Actual WLAN systems need to get the CSI for the MU-MIMO transmission and MIMO detection. Realistic channel conditions has channel estimation error and CSI feedback error. During the CSI feedback, in order to reduce CSI overhead, the number of bits are reduced by channel compression at the receiver side.

In this paper, we evaluate the performance of the next generation standard 802.11ac WLAN system. We measure these improvements when realistic channel conditions are applied. We compare the performance of CI and BD precoding methods paired with various MIMO detection techniques. From the simulation results, we show the effectiveness of BD precoding compared to CI precoding in the 802.11ac WLAN system.

The rest of the paper is organized as follows. Section II shows the 802.11ac WLAN system in detail. In Section III, we explain about MU-MIMO transmission techniques. In section IV, we shows simulation results 802.11ac WLAN system in realistic channel conditions. Finally, section V presents the conclusions of this research.

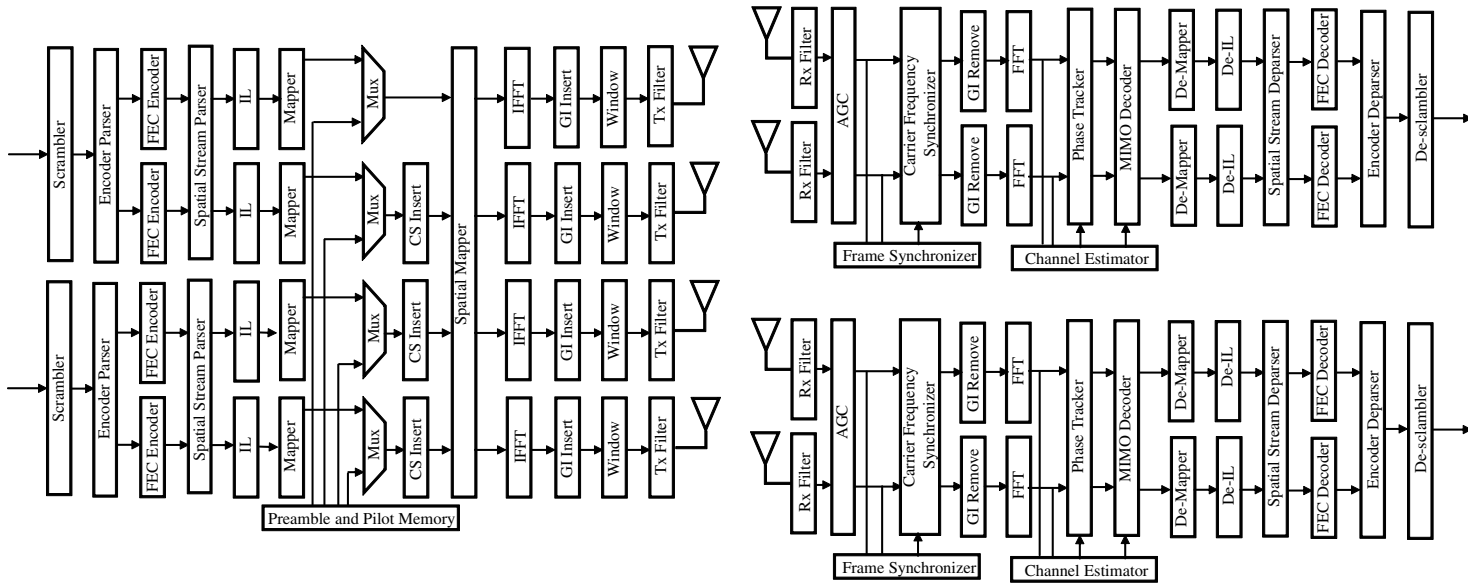


Fig. 1. 802.11ac Wireless LAN System Architecture (2 user case)

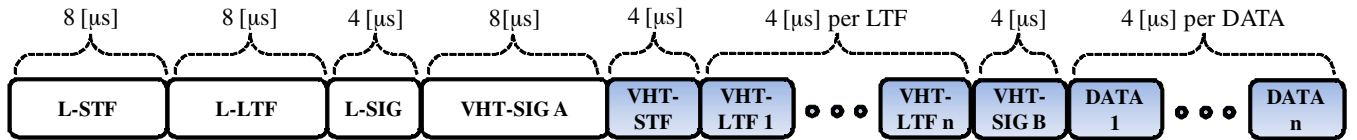


Fig. 2. VHT Packet Format for 802.11ac Wireless LAN System

TABLE I
SPECIFICATIONS OF THE 802.11AC SIMULATOR

PARAMETER	Value
Carrier Frequency	5.25 [GHz]
Baseband Bandwidth	20, 40, 80 [MHz]
PPDU Format	VHT Mode
GI Length	400, 800 [ns]
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding Rate	1/2, 2/3, 3/4, 5/6
Error Collection	Soft Decision Viterbi Decoder
Number of TX Antenna	1 – 8
Number of RX Antenna	1 – 8
Number of Stream	1 – 8
Number of User	1 – 4
MCS	0 – 7
MU-MIMO Transmission	CI, BD
MIMO Decoder	MMSE, V-BLAST MMSE, LRA MMSE
Max Data Rate	2,600 [Mbps]

II. A NEXT GENERATION GIGABIT WLAN SYSTEM

A. 802.11ac WLAN System Architecture

Block diagram of transmitter and receiver of the 802.11ac WLAN system for 2 user case is shown in Fig. 1. Due to the user streams being received independently by different receivers, the minimum number of scramblers, forward error correction (FEC) blocks and interleavers are also dictated by the number of active STAs N_{USR} . In linear precoders, only one weight matrix is relevant for beamforming. In 802.11n, the beamforming matrix is an input to the spatial expansion

block in the transmitter. That is, if beamforming is enabled, the beamforming matrix is used. Otherwise, the transmitter uses an identity or pseudo-identity matrix.

Table I lists the specifications of the 802.11ac simulator. This is a simulator implementing all mandatory specification of 802.11ac including the optional MU-MIMO transmission, up to 8 spatial stream transmission and short guard interval (SGI). Our simulator implemented CI and BD for MU-MIMO transmission, MIMO decoder implemented MMSE, V-BLAST MMSE and LRA MMSE detection.

B. VHT Packet Format

The packet format of 802.11ac which is adopted in this paper is shown in Fig. 2. The non-shaded area is always single stream and is transmitted omnidirectionally while the shaded area is generally multi-stream and is precoded for downlink MU-MIMO beamforming. Here, legacy short training field (L-STF), legacy long training field (L-LTF) and legacy signal field (L-SIG) fields are all for the purpose of compatibility with legacy 11a/n devices. VHT-SIG A while omnidirectional is important for MU-MIMO beamforming to inform the participating STAs of the parameters of the directional portion of the packet. VHT-STF is a training field whose primary purpose is for MIMO data power computation. This is necessary because huge power variation can occur between the single stream and multi-stream portions of the packet which necessitates the reset of the automatic gain control (AGC). VHT-LTFs on the other hand are used to compute the MIMO Channel. The computed

channel is either sent back to the AP during sounding or used for symbol detection when receiving a MU transmission. Information regarding user specific modulation and coding rates schemes (MCS) and per user DATA field lengths on the other hand are present in the per station beamformed VHT-SIG B field seen in Fig. 2.

III. PRECODING ALGORITHMS

The transmitter computes a beamforming weight matrix that will prevent signals of one STA to interfere with other STAs. Let us consider the multiuser MIMO system where the STA has N_{TX} antennas, each STA has N_{RX} antennas, and the number of existing STAs is N_{USR} . When an $N_{RX} \times N_{TX}$ channel matrix of the i^{th} user is defined as $\mathbf{H}_i$, an $N_{RX}N_{USR} \times N_{TX}$ channel matrix can be expressed as

$$\mathbf{H} = [\mathbf{H}_1^T, \mathbf{H}_2^T, \dots, \mathbf{H}_i^T, \dots, \mathbf{H}_{N_{USR}}^T]^T. \quad (1)$$

$\mathbf{H}$ follows a complex Gaussian distribution with mean zero and variance one (Rayleigh distribution). In general, the received signal of the i^{th} user can be expressed as

$$\mathbf{y}_i = \mathbf{H}_i \mathbf{x} + \mathbf{n}_i. \quad (2)$$

$\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_i, \dots, \mathbf{x}_{N_{USR}}]^T$ is the transmit signal vector, and $\mathbf{n}_i$ is the noise from the receiver. We assume that for each of the K users, this noise is identically distributed, independent, equal variance and zero mean Gaussian noise. Hence $\mathbf{R}_n = E[\mathbf{n}\mathbf{n}^H] = \sigma_n^2 \mathbf{I}$.

A. Channel Inversion

CI achieves MU-MIMO transmission by multiplying signals at access points by the inverse of the channel matrix $\mathbf{H}$, which represents CSI from AP to each STAs. The easiest precoding scheme called CI precoding is expressed as

$$\mathbf{x} = \frac{\mathbf{H}^{-1} \mathbf{u}}{\sqrt{\gamma_{CI}}}, \quad (3)$$

where $\mathbf{u}$ is the vector of symbols intended for the N_{USR} users while $\mathbf{x}$ is the precoded transmit symbol vector. The denominator $\gamma_{CI} = \mathbf{u}^H (\mathbf{H}\mathbf{H}^H)^{-1} \mathbf{u}$ normalizes the transmit power to a constant value. This is due to the fact that the inverse of the channel matrix used as the weight matrix in CI has singular values with a wide distribution [14]. The wide distribution of the singular values of the inverse increases the precoded signal power.

B. Block Diagonalization

BD is a generalization of channel inversion techniques when there are multiple antennas at each STAs. We first consider an $N_{RX}(N_{USR} - 1) \times N_{TX}$ channel matrix

$$\tilde{\mathbf{H}}_i = [\mathbf{H}_1^T, \dots, \mathbf{H}_{i-1}^T, \mathbf{H}_{i+1}^T, \dots, \mathbf{H}_{N_{USR}}^T]^T. \quad (4)$$

Let the singular value decomposition (SVD) of $\tilde{\mathbf{H}}_i$ be

$$\tilde{\mathbf{H}}_i = \tilde{\mathbf{U}}_i \tilde{\Sigma}_i \tilde{\mathbf{V}}_i^H = \tilde{\mathbf{U}}_i \begin{bmatrix} \tilde{\Sigma}_i & \mathbf{0} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{V}}_i^b & \tilde{\mathbf{V}}_i^n \end{bmatrix}^H, \quad (5)$$

where $\tilde{\mathbf{U}}_i$ and $\tilde{\mathbf{V}}_i$ are the left singular vector matrix and the matrix of singular values of $\tilde{\mathbf{H}}_i$, respectively, and $\tilde{\mathbf{V}}_i^b$ and $\tilde{\mathbf{V}}_i^n$ denote the right singular matrices each corresponding to non-zero singular values and zero singular values ($N_{TX} - \text{rank}(\tilde{\mathbf{H}}_i)$) singular vectors in the nullspace of $\tilde{\mathbf{H}}_i$, respectively. $\tilde{\mathbf{V}}_i^n$ will satisfy the null constraint, since it will produce zero interference at the other users. Assuming that $\tilde{\mathbf{H}}_i$ is full rank, the AP requires that the number of transmit antennas is at least the sum of all STAs receive antennas to satisfy the dimensionality constraint required to cancel interference for each STAs. The weight matrix of BD is expressed as

$$\mathbf{W}_{BD} = [\tilde{\mathbf{V}}_1^n, \tilde{\mathbf{V}}_2^n, \dots, \tilde{\mathbf{V}}_i^n, \dots, \tilde{\mathbf{V}}_{N_{USR}}^n] \\ \tilde{\mathbf{H}} = \begin{bmatrix} \mathbf{H}_1 \tilde{\mathbf{V}}_1^n & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{H}_{N_{USR}} \tilde{\mathbf{V}}_{N_{USR}}^n \end{bmatrix}. \quad (6)$$

This precoding scheme is called BD precoding and is done using

$$\mathbf{x} = \frac{\mathbf{W}_{BD} \mathbf{u}}{\sqrt{\gamma_{BD}}}. \quad (7)$$

The denominator $\gamma_{BD} = \mathbf{u}^H (\mathbf{W}_{BD} \mathbf{W}_{BD}^H)^H \mathbf{u}$ normalizes the transmit power to a constant value. Under the BD precoding, an effective MIMO channel can be equivalently regarded as a single-user MIMO (SU-MIMO) environment.

IV. SIMULATION RESULTS

In this section, we investigate the performance of linear precoding schemes with realistic channel condition. Table II lists the rest of simulation parameters of all environment.

A. BER and PER Characteristic

In this paper, we examined is the bit error rate (BER) and packet error rate (PER) performance. First, Fig. 3 shows the uncoded (before Viterbi decoder input) BER performance of the CI and BD.

In Fig. 3, we observe that high performance MIMO decoders such as LRA MMSE decoder, improve the uncoded BER performance of the BD precoding. However, it does not improve the uncoded BER performance of the CI precoding. Because the CI precoding is an inverse of the channel matrix, the effective channel matrix becomes the diagonal matrix at the receiver side. On the other hand, the effective channel matrix of the BD precoding is a block diagonal matrix. Hence MIMO decoders can take advantage of the diversity present in the inter stream interference within a single user.

TABLE II
SIMULATION PARAMETERS

PARAMETER	Value
Packet Format	80 [MHz] VHT Mode
Number of Byte	1,000 [byte]
GI Length	800 [ns]
Antenna Configuration	$4 \times [2, 2]$ MIMO (2 user)
Spatial Mapping	Direct Mapping
MCS	4 (16-QAM : 3/4), 7 (64-QAM : 5/6)
Channel Model	TGn Channel Model B, D
Number of Packets	10,000
Channel Estimation	"Real Condition"
Carrier Frequency Sync.	"Real Condition"
Frame Sync.	"Ideal Condition"
Power Amplifier Impairment	"on"
DAC Impairment	"on"
ADC Impairment	"on"
Phase Noise Impairment	"on"

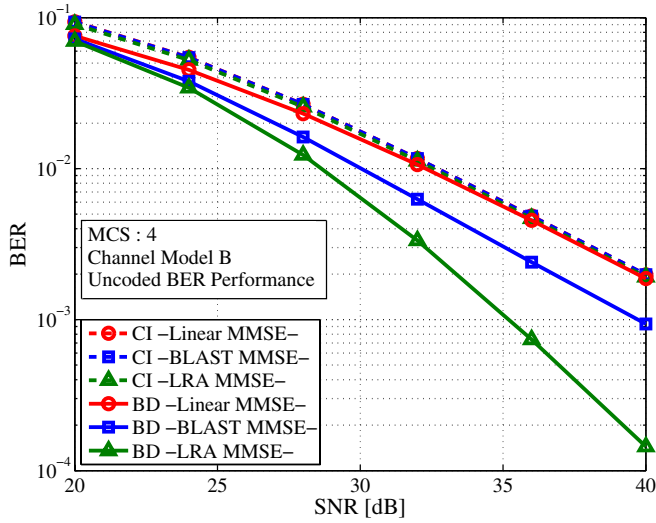


Fig. 3. Uncoded BER Performance of CI vs. BD (MIMO Decoder: MMSE, V-BLAST MMSE and LRA MMSE, MCS: 4, Channel Model B)

Figs. 4 and 5, show the PER characteristic of the CI and BD in the cases when the channel model B. Additionally, Figs. 6 and 7, show the PER characteristic of the CI and BD in the cases when the channel model D.

When compared the channel model B and D of all cases, the PER performance measured the channel model D is better than the channel model B. The channel model B is high correlated, the wide distribution of the singular values of the inverse increases the precoded signal power at the transmitter, and noise enhancement at the receiver side.

We considered the PER performance of each MU-MIMO transmission methods when MIMO decoder is changed. When the Linear MMSE and the V-BLAST MMSE decoder are compared, the PER performance measured in the Linear MMSE is better than the V-BLAST MMSE. While the uncoded BER performance of V-BLAST MMSE is better than Linear MMSE, performance degradation caused by error propagation limits the performance of coded V-BLAST MMSE [15]. Also, we observe the substantial improvement of the PER performance

of the BD precoding when using the LRA MMSE decoder. Regarding, This little improvement for CI was seen when the LRA MMSE was used.

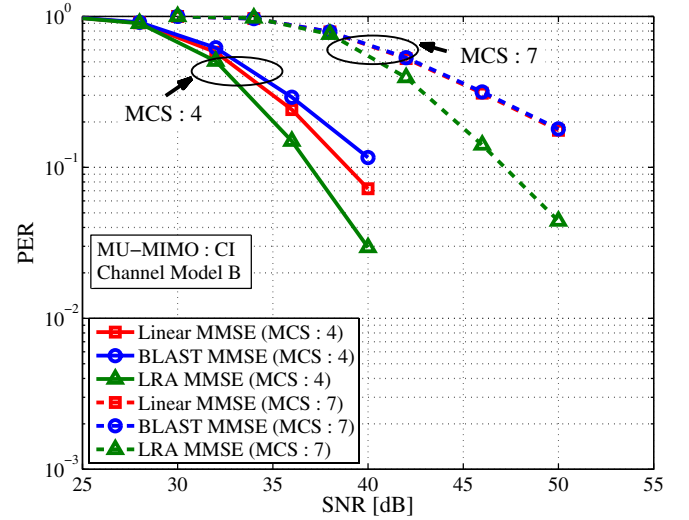


Fig. 4. PER Performance (MU-MIMO: CI, MIMO Decoder: MMSE, V-BLAST MMSE and LRA MMSE, MCS: 4/7, Channel Model B)

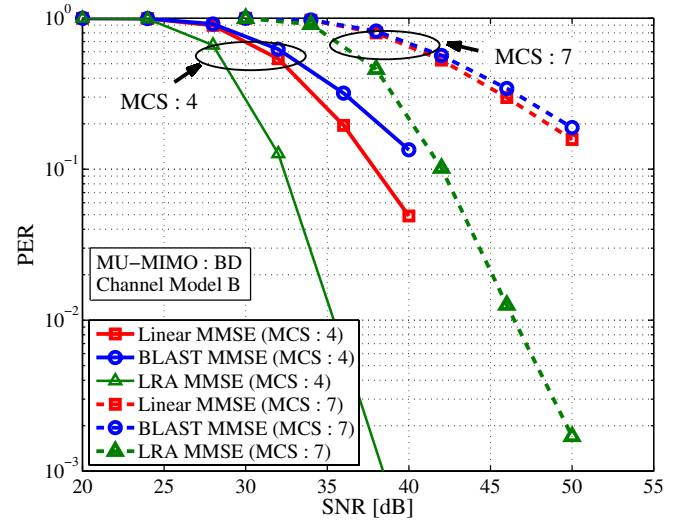


Fig. 5. PER Performance (MU-MIMO: BD, MIMO Decoder: MMSE, V-BLAST MMSE and LRA MMSE, MCS: 4/7, Channel Model B)

V. CONCLUSION

In this paper, we investigated the performance of MU-MIMO 802.11ac WLAN system. From the simulation results, PER performance of the BD precoding can be improved by the MIMO decoder. The BD precoding is available MU-MIMO transmission method. Future work on this research includes implementation of other MU-MIMO transmission methods, as well as the design of the optimal De-Mapper after MIMO decoder. Also, We will do an register transfer level (RTL) design of the proposed 802.11ac WLAN system.

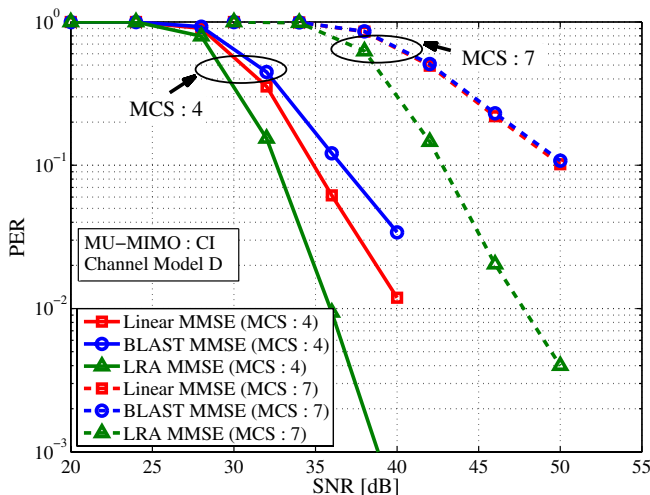


Fig. 6. PER Performance (MU-MIMO: CI, MIMO Decoder: MMSE, V-BLAST MMSE and LRA MMSE, MCS: 4/7, Channel Model D)

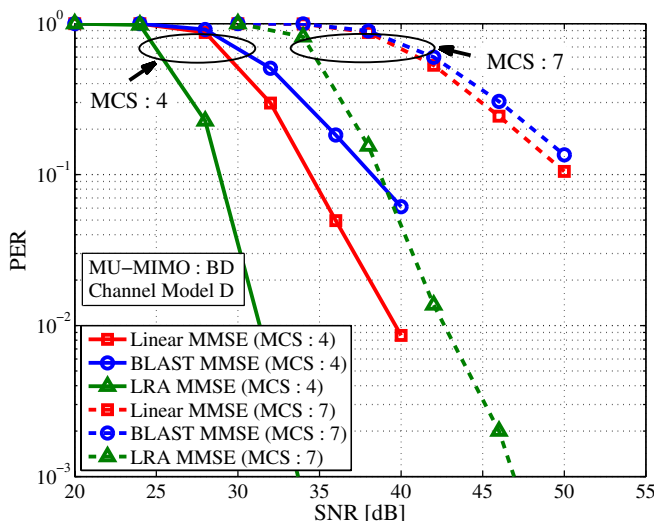


Fig. 7. PER Performance (MU-MIMO: BD, MIMO Decoder: MMSE, V-BLAST MMSE and LRA MMSE, MCS: 4/7, Channel Model D)

VI. ACKNOWLEDGMENT

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VII. 802.11AC STANDARDIZATION ACTIVITY REPORT

Our research group has made several proposals to the Committee IEEE 802. Two proposal techniques was successfully adopted [16], [17].

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