MIMO Modes in ieee802.11ac

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **MIMO Modes in ieee802.11ac**, submitted by **Mudavath Srinivas**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

There has been recently an increasing interest of exploring advanced techniques for beyond 4G wireless communication systems to meet the requirement of high data rate, high capacity and high mobility. Exploiting diversity techniques within an OFDM system is rather promising to meet this requirement. Some of the techniques are Beamforming, Higher modulation, Channel Bonding etc. In this dissertation, the Beamforming technique is therefore investigated in order to improve the bit error rate performance of MU Downlink wireless communication systems specifically those using multiple transmitter and receiver antennas.

This thesis is organized in three parts. In the first part of the thesis, we study the *litrature on ieee802.11ac*. It operates at 5GHz with 20MHz or 40MHz or 80MHz or 160(80+80)MHz channel width. It uses upto 256 QAM Modualtion. which increases throughtput to a large extent. In the second part of the thesis, we study the *SU-MIMO OFDM with ZF/MMSE Receiver*. In the third part of the thesis, we study the *MU-MIMO OFDM with ZF-Beamforming*.

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ABBREVIATIONS

SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
BER	Bit Error Rate
DoF	Degrees of Freedom
ICBM	Interference Cancelling Block Modulation
AWGN	Additive White Gaussian Noise
OFDM	Orthogonal Frequency Division Multipleing
SU-MIMO	Single User-Multiple Input Multiple Output
MU-MIMO	Multi User-Multiple Input Multiple Output
CP	Circular Prefix
ZF	Zero Forcing
MMSE	Minimum Mean Square Error
IUI	Inter User Interference
ICI	Inter Carrier Interference
CSI	Channel State Information
ISI	Inter Symbol Interference
IFFT	Inverse Fast Fourier Transform
FFT	Fast Fourier Transform
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
ML	Maximum Likelihood
MD	Minimum Distance
SVD	Singular Value Decomposition
Tx	Transmitter
Rx	Receiver
dB	Decibel

NOTATION

A	Matrix
A^T	Transpose of a Matrix
A^H	hermitian Transpose of a Matrix
A^{-1}	Inverse of a Matrix
I_N	Identity Matrix
Log	Natural Logarithm
$\mathbb{C}$	Set of all Complex numbers
$\mathbb{R}$	Set of all Real numbers
$\mathbb{C}^{\mathbb{K}\times\mathbb{N}}$	Set of KxN matrices with complex entries
$\mathcal{CN}(\mu, \sigma^2)$	Complex Gaussian Distribution with mean μ and variance σ^2
j	j^{th} transmitter
j	j^{th} Receiver.

Part I

litrature on ieee802.11ac

CHAPTER I

litrature on ieee802.11ac

1 Itroduction

Wireless Local Access Networks have become very popular in the past decade. It replaced cable Local Access Networks (LANs) in many applications, especially for home usages. It was possible to provide Internet services in public areas. The IEEE 802.11 series of standards for WLAN have shown great success since it started in the late 1990s. Until a recent time, these WLANs have been mainly used for Internet browsing, email, and other light load applications. Today the demand for throughput is increasing and users want to be able to stream HD videos, music, or transfer large amounts of data, participate in multi-player games, or make video conferences etc. These demands are met by two new standards for WLANs, IEEE 802.11ac and 11ad, operating on the 5 GHz band and the 60 GHz band, respectively. The 11ac is the new standard built on the previous successful 11n standard. The 11ac will be able to deliver a high performance comparable to wired networks by expanding the 11n in many aspects including the following features:

- operates on only 5GHz Band
- Channel bounding up to 160 MHz bandwidth.
- Up to 8 spatial streams.
- Higher orders of modulations up to 256-QAM.
- support for Downlink MU MIMO Technology with Beamforming.

The 11ac standard will be able to achieve a data rate of at-least 1Gbps and a datarate of 6.93 Gbps using 160 MHz channel bandwidth, 8 spatial streams, 256-Quadrature Amplitude Modulation (QAM) and Short Guard Intervals (GIs). The 11ac was made backward compatibility with the previous standards 11a and 11n.

2 OFDM in IEEE 802.11ac

In multi-carrier systems such as FDM, the sub-carriers are totally separated with guard intervals to avoid Inter Carrier Interference from other adjacent subcarriers. This separation in the spectrum causes a huge waste in the frequency spectrum. An OFDM system is similar to FDM systems, except that it split the spectrum into adjacent overlapping sub-carriers, which saves a big portion of the spectrum. and therefore OFDM is spectrally efficient. But it is sensitive to frequency offset which might arise during frequency synchronisation and a problem of PAPR exist.

The IEEE 802.11ac 5GHz bandwidth is split into subcarriers with a subcarrier spacing of 312.4 kHz[2]. Most of the sub-carriers are used for carrying data samples. Few sub-carriers are assigned for pilots, which are used as a reference for phase and frequency shift corrections of symbols during transmission. These pilot sub-carriers are set apart to make a good estimation over the whole bandwidth. The sub-carriers at the middle of the bandwidth (DC) are null-ed to reduce problems in analogue baseband circuits, and the sub-carriers at the higher and lower edges of the bandwidth are nulled to avoid interference from adjacent channels. TableI.1 shows number of OFDM subcarriers at different Channel widths. The OFDM symbols must be lead by a Guard Interval

Table I.1: Number of OFDM subcarriers in 11ac.

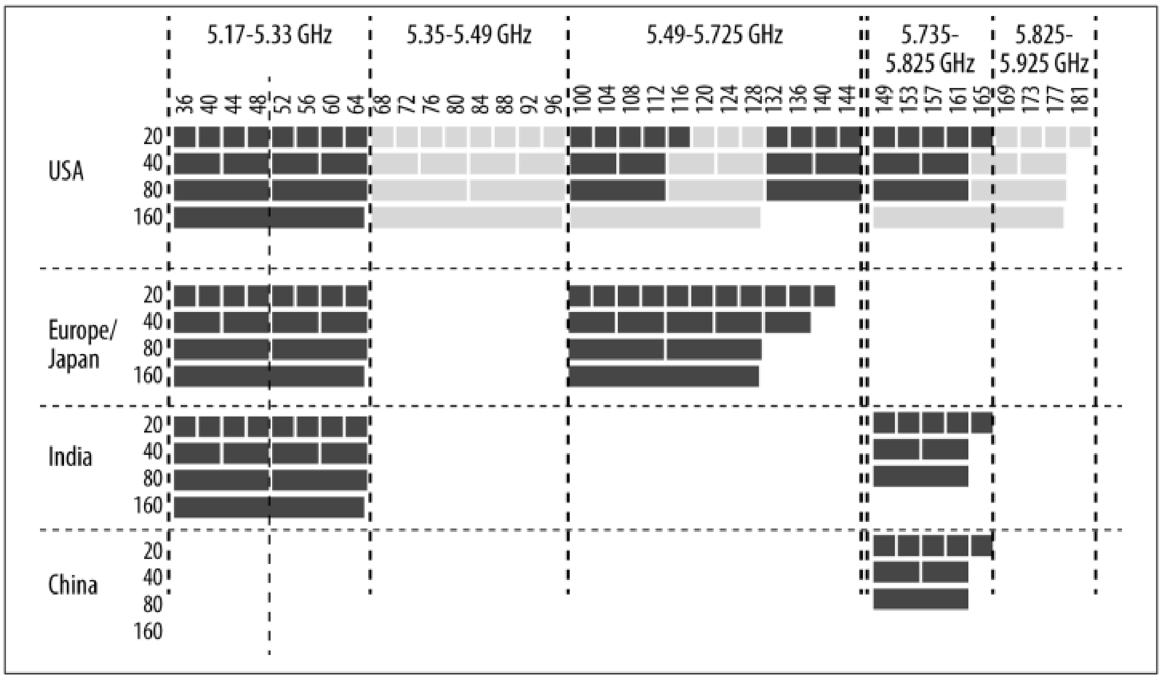
Bandwidth(MHz)	20	40	80	160 (80+80)
FFT Size	64	128	256	512
Number of SC's	52	108	234	468
Number of Pilot SC's	4	6	8	16
Total Number of SC's	56	114	242	484
Transmission SC's	$\pm(1-28)$	$\pm(2-58)$	$\pm(2-122)$	$\pm(6-126), \pm(130-250)$

to provide resistance to ISI, and time synchronization errors. In the IEEE 802.11 standards, the symbols duration is $4\mu s$, 20% this duration (800ns) is the GI, which carries a cyclic prefix of the signal. Considering a small symbol timing inaccuracy, this GI allows the receiver to handle a channel delay spread of 600 ns.

2.1 Channel Bonding

FigureI.1 shows available channels numbers across globe. We can notice that more than 8 consecutive 20MHz channels can be found. Channel Bonding allows to combine these consecutive 20MHz channels and make into a 40/80/160MHz channel. sometimes it might not be possible to get 8 consecutive 20MHz channels, so 11ac allows to combine two 80MHz channels to a 160MHz channel.

Figure I.1: Available Channel Maps.



3 IEEE.11ac Specifications

3.1 Modulation and Coding

R=1/2 transmits one user data bit for every two bits on the channel. Higher code rates have more data and less redundancy at the cost of not being able to recover from as many errors. In 802.11ac, modulation and coding are coupled together into a single number, the MCS index. Selecting a modulation and coding set (MCS) is much simpler in 802.11ac than it was in 802.11n. Rather than the 70-plus options offered by 802.11n, the 802.11ac specification has only 10(see TableI.2). The first seven MCS Index values are mandatory. error correcting code BCC is mandatory and LDPC is optional. MCS Selection is valid only if the number of coded bits per subcarrier must be an integer multiple of the number of encoding streams. the number of coded bits per encoding stream must be an integer multiple of the denominator in the code rate.

Table I.2: MCS Values for 11ac.

MCS Index Values	Modulation	Code Rate
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16-QAM	1/2
4	16-QAM	3/4
5	64-QAM	2/3
6	64-QAM	3/4
7	64-QAM	5/6
8	256-QAM	3/4
9	256-QAM	5/6

3.2 PHY-Level Framing

The physical layer framing for 802.11ac is compatible with previous 802.11 PHYs and called as VHT Frame. the format of the VHT physical layer frame is similar to the mixed-mode format used in 802.11n, and it begins with the same fields as 802.11a frames. a new physical layer header was required to enable multi-user MIMO transmissions because the 802.11n HT-SIG header field was not readily extensible to new channel widths or large numbers of spatial streams. this new header will be able to describe the number of spatial streams and enable multiple receivers to set up to receive their frames.

3.3 Data Rates of 11ac

Data rates are determined by the combination of channel width, modulation and coding, number of spatial streams, and the guard interval.

- Each spatial stream adds proportionally to throughput.

- Wider channels also increase throughput proportionally.
- Higher modulation increases throughput proportionally with decrease in BER.

From TableI.3, one can get the speed of any MCS rate, take the basic 20 MHz stream, multiply by the number of spatial streams, and then multiply that result by a channel correction factor.

Table I.3: 802.11ac data rate matrix

MCS value	**20 MHz data rate (1SS, short GI)**	**Spatial stream multiplication factor**	**Channel width Multiplication Factor**	**Maximum 40 MHz rate(8 SS, short GI)**	**Maximum 80 MHz rate(8 SS, short GI)**	**Maximum 160 MHz rate(8 SS, short GI)**
MCS 0	7.2 Mbps	x2 for 2 streams	x1.0 for 20 MHz	120.0 Mbps	260.0 Mbps	520 Mbps
MCS 1	14.4	x3 for 3 streams	x2.1 for 40 MHz	240.0	520.0	1040.0
MCS 2	21.7	x4 for 4 streams	x4.5 for 80 MHz	360.0	780.0	1560.0
MCS 3	28.9	x5 for 5 streams	x9.0 for 160 MHz	480.0	1040.0	2080.0
MCS 4	43.3	x6 for 6 streams		720.0	1560.0	3120.0
MCS 5	57.8	x7 for 7 streams		960.0	2080.0	4160.0
MCS 6	65.0	x8 for 8 streams		1080.0	2340.0	4680.0
MCS 7	72.2			1200.0	2600.0	5200.0
MCS 8	86.7			1440.0	3120.0	6240.0
MCS 9	96.3			1600.0	3466.7	6933.3

3.4 Comparison of 802.11ac Data Rates to Other 802.11 PHYs

The tableI.4 compares the top data rate, not necessarily a typical data rate. 802.11ac speeds shown are with 256-QAM, which may not always be achievable in real-world.

Table I.4: Speed comparisons between different 802.11 standards

Technology	**20 MHz**	**40 MHz**	**80 MHz**	**160 MHz**
802.11b	11 Mbps			
802.11a/g	54 Mbps			
802.11n(1 SS)	72 Mbps	150 Mbps		
802.11ac(1 SS)	87 Mbps	200 Mbps	433 Mbps	867 Mbps
802.11n(2 SS)	144 Mbps	300 Mbps		
802.11ac(2 SS)	173 Mbps	400 Mbps	867 Mbps	1.7 Gbps
802.11n(3 SS)	216 Mbps	450 Mbps		
802.11ac(3 SS)	289 Mbps	600 Mbps	1.3 Gbps	2.3 Gbps
802.11n(4 SS)	289 Mbps	600 Mbps		
802.11ac(4 SS)	347 Mbps	800 Mbps	1.7 Gbps	3.5 Gbps
802.11ac(8 SS)	693 Mbps	1.6 Gbps	3.4 Gbps	6.9 Gbps

3.5 Mandatory PHY Features

802.11ac is a complex standard with a large number of protocol features. Table I.5 classifies the protocol features as either mandatory or optional.

Table I.5: Feature classification of PHY features

Feature	Mandatory Optional	Comments
Support for VHT format of frames	Mandatory	
20, 40 MHz channels	Mandatory	These channel widths were required in previous PHY standards.
80 MHz channels	Mandatory	
160 MHz and 80+80MHz operation	Optional	Not supported by first wave of devices.
Single-stream operation MCS 0 through 7	Mandatory	
Single-stream operation MCS 8 and 9	Optional	Optional, but likely to be widely supported.
Two-stream operation	Optional	Mandatory in WFA program for anything other than a battery-operated mobile AP, just as with 802.11n certification.
Three-stream operation	Optional	
Four-stream operation	Optional	
Five- to eight-stream operation	Optional	Not likely to be supported until later product releases.
Support for MCS 8 and 9 (256-QAM) with more than one stream	Optional	
Short guard interval of 400 ns	Optional	Although optional, this will be widely supported. (Approximately 3/4 of WFA-certified 11n devices implement the feature.)
LDPC	Optional	Likely to be supported in tandem with 256-QAM.
STBC	Optional	Likely to be moderately well supported, but most products will implement only single-stream (2x1) operation.

4 Beamforming in 802.11a

Traditionally, access points have been equipped with omnidirectional antennas, which are so named because they send energy in all directions. An alternative method of transmission is to focus energy toward a receiver, called as *beamforming*. beamforming focus increases receive power, and therefore increases the signal-to-noise ratio and data rates. Beamforming, at short ranges the signal power is high enough that the SNR will support the maximum data rate. At long ranges, beamforming does not offer much gain over an omnidirectional antenna.

Any device that focuses its transmitted frames is called a *beamformer*, and a receiver of such frames is called a *beamformee*. for beamforming technique, *Steering Matrix* must be known at the transmitter i.e. CSIT. *Steering Matrix* is calculating with Channel Sounding Operation. Channel sounding consists of three major steps:

- The beamformer begins the process by transmitting a Null Data Packet Announce ment frame, which is used to gain control of the channel and identify beamformees. Beamformees will respond to the NDP Announcement, while all other stations will simply defer channel access until the sounding sequence is complete.
- Then beamformer sends the NDP Announcement with a null data packet. The value of an NDP is that the receiver can analyze the OFDM training fields to calculate the channel response, and therefore the steering matrix. For mult-user transmissions, multiple NDPs may be transmitted.
- The beamformee analyzes the training fields in the received NDP and calculates a feedback matrix V.
- The beamformer receives the feedback matrix and calculates the steering matrix to direct transmissions toward the beamformee.

Part II

SU-MIMO OFDM With ZF/MMSE Receiver

CHAPTER II

SU-MIMO OFDM With ZF/MMSE Receiver

1 Introduction

The term MIMO is the systems with multiple antennas at both transmitter and the receiver. The use of multiple antennas allows independent channels to be created in space and it is possible to achieve spatial diversity, which can be created without any additional bandwidth and transmit power. In addition to providing spatial diversity, antenna arrays can be used to focus energy (beamforming) or create multiple parallel channels for carrying unique data streams (spatial multiplexing). When multiple antennas are used at both the transmitter and the receiver, it is commonly referred as MIMO system. These systems can be used to:

- the system reliability (decrease the bit or packet error rate).
- Increase the achievable data rate and hence system capacity.
- Increase the coverage area.
- Decrease the required transmits power.

However, these four desirable attributes usually compete with one another. For example, an increase in data rate will often require an increase in either the error rate or transmit power.
It is one of the major developments in wireless communication system and is internationally researched[1-8]. The signals are transmitted in multiple paths and therefore introduce spatial diversity on the data stream in the channel. It is unlikely that all the paths would encounter severe fading at the same time which allows the MIMO scheme to improve the signal strength in a natural wireless environment.

MIMO systems[3] have become attractive trends for broadband wireless communications such as wireless LAN(IEEE 802.11n, IEEE 802.11ac), WCDMA and WiMAX (IEEE 802.16); this is partly due to the significant increase in data throughput and link range without the need to either increase the transmit power or the system bandwidth[8].

In this chapter, we investigate a $N \times M$ MIMO systems under L-Tap Rayleigh channel using different modulation techniques. First MIMO System Model is described. This MIMO system is then combined with an OFDM signal with parameters specified in IEEE 802.11ac standard. The results obtained from MATLAB simulation in a Rayleigh multipath environment were discussed.

2 MIMO System and MIMO Detection

2.1 SU-MIMO OFDM System with IEEE 802.11AC Starndards

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most popular modulation schemes where multiple symbols are transmitted simultaneously on a channel bandwidth without ISI . It is used in wireless LAN standards like 802.11a/g/n/ac. The latest standard IEEE 802.11ac gives high throughput and reliability over older standards like 802.11a/g/n. with data rates up to 6Gbps. This is achieved through the combination of OFDM with MIMO techniques.

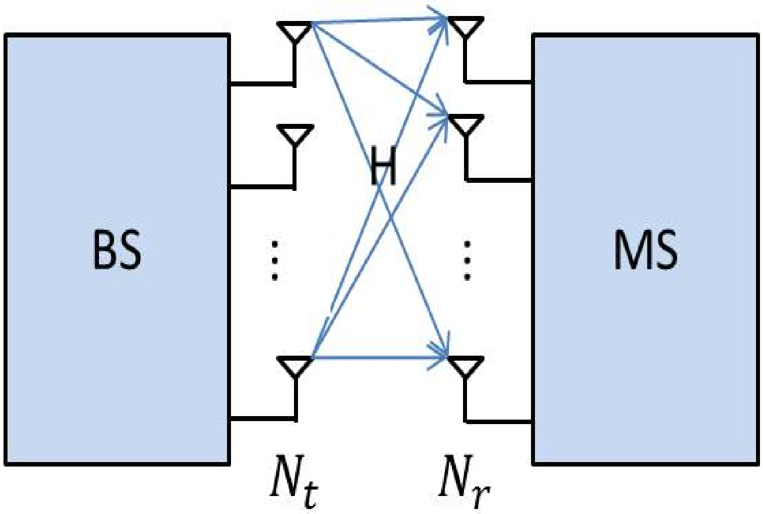
An understanding on how to interpret 802.11ac standards is required to fully understand the theory behind increased throughput. As an example, the IEEE 802.11ac standard is shown in Table1 and examined further.
From Table1, it is noted that the total number of subcarriers is 64 with a sampling frequency of 20MHz. In the 802.11ac standard operation at 40MHz is supported. Only 56 of these sub-carriers are used to transmit the actual data sequence with the symbol duration $3.2\mu s$, therefore the total spacing between sub carriers is 312.5kHz. 25 percentage of FFT are used as cyclic prefix (i.e. 16 samples), therefore 0.8Îijs is the duration of the cyclic prefix leading to total symbol duration of $4\mu s$.

2.2 System Model

FigureII.1 shows a typical MIMO system. Consider a down-link SU-MIMO OFDM system comprising N_t transmit and N_r receive antennas.

We consider a single-cell SU down-link system with N_t transmit antennas at the base station(BS) and mobile user equipped with N_r receive antennas. The system op-

Figure II.1: SU MIMO System



erates with N_c OFDM subcarriers, N_d of which are used to transmit user data while the rest correspond to pilots and guard bands(zero carriers). Receiver knows the Channel state information(CSI). For simplicity, consider 2×2 System. ($N_T = 2$ and $N_R = 2$) $H(q)$ represents the L-Tap channel gain matrix corresponding to the user over q^{th} sub-carrier.

Table II.1: Table1:IEEE802.11ac Parameters

Parameter	Value
FFT Size	64
Used Sub-Carriers	56
Cyclic Prefix	n/4
Subcarrier Spacing	312.5kHz
Index of used subcarriers	(-28 t0 -1, +1 to +28)
Data Symbol	3.2us

As shown in Figure II.2. The encoder takes a single stream of binary input data and transforms it into N_t parallel streams of encoded bits followed by inter-leavers and symbol mappers. After the symbol mappers, the m^{th} IFFT input at transmit antenna i is denoted by $X^i_m, m = 1, 2, ...N, i = 1, 2..., N_t$. After the IFFT, the n^{th} OFDM symbol at transmit antenna i denoted by x^i_n is given by

$$x^i_n = 1/\sqrt{N} \sum_{m=1}^{N} X^i_m e^{j2\pi nm/N}, \quad n = 1, ...N \quad i = 1, 2...n_t \tag{II.1}$$

Now, Cyclic Prefix is added. Here the cyclic prefix is omitted for simplicity. Let $h^{j,i}_{n,l}$ be the impulse response of l^{th} multipath component at time n(on subcarrier q) from transmit antenna i to receive antenna j. the n^{th} received signal at antenna j is y_n^j represented as follows:

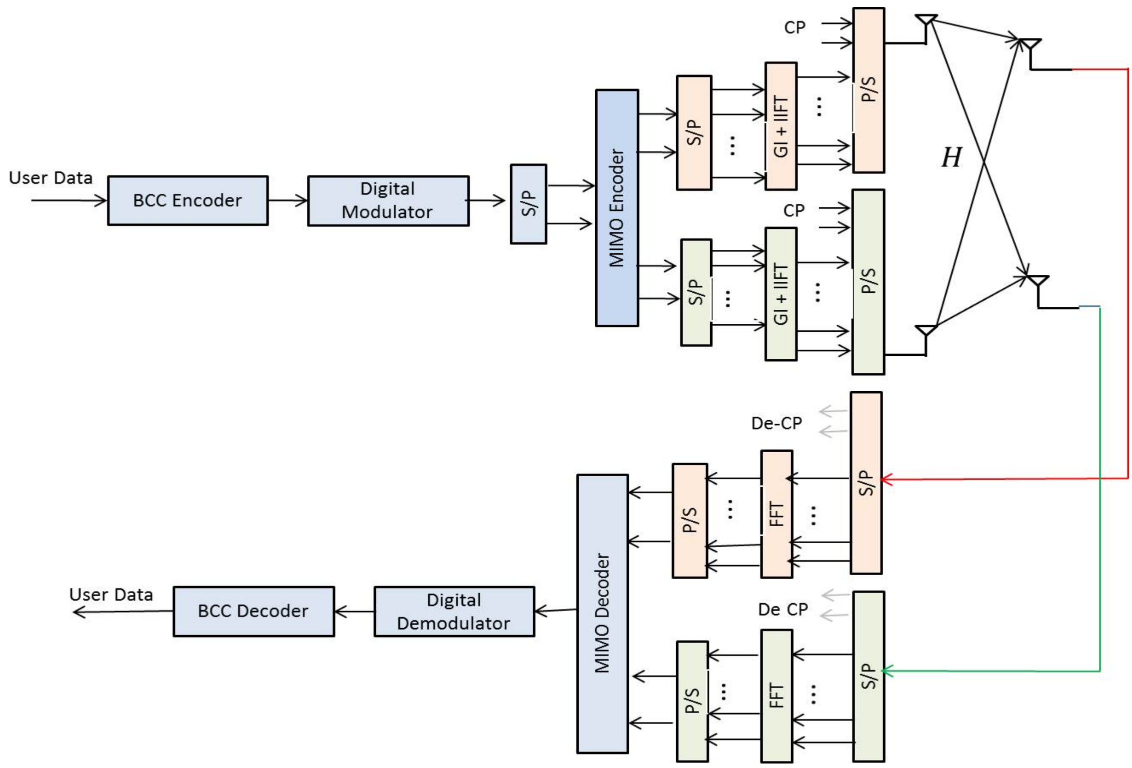
$$y_n^j = \sum_{i=1}^{N_t} \sum_{l=1}^{L} h_{n,l}^{j,i} x_{n-l}^i + w_n^j \quad n = 1, 2, ...N \quad j = 1, 2...N_r \tag{II.2}$$

where w_n^j represents additive white Gaussian noise of j^{th} receive antenna at time n. Note that y_n^j is the sum of transmitted symbols from all transmit antennas.

$$y_n^j = \sum_{i=1}^{N_t} \sum_{l=1}^{L} h_{n,l}^{j,i} 1/\sqrt{N} \sum_{m=1}^{N} X_m^i e^{j2\pi(n-l)m/N} + w_n^j \quad n = 1, 2, ...N \quad j = 1, 2...N_r \tag{II.3}$$

By defining, $H_{n,(m)}^{j,i}$ as N point FFT

Figure II.2: System Model of OFDM data Transmission



$$H_{n,(m)}^{j,i} = \sum_{l=1}^{L} h_{n,l}^{j,i} e^{-j2\pi nm/N}, \quad n, m = 1, ...N \quad i = 1, 2...n_t \tag{II.4}$$

Let Y_m^j is the FFT of received signal and W_m^j is FFT of AWGN.

$$Y_m^j = 1/\sqrt{N}\sum_{n=1}^{N} y_n^j e^{j2\pi nm/N}, \quad m = 1,...N \quad j = 1,2...n_t \tag{II.5}$$

$$W_m^j = 1/\sqrt{N}\sum_{n=1}^{N} w_n^j e^{j2\pi nm/N}, \quad m = 1,...N \quad j = 1,2...n_t \tag{II.6}$$

now, received signal is

$$Y_n^j = \sum_{i=1}^{N_t} 1/N \sum_{n=1}^{N} H_{n,(m)}^{j,i} X_m^i + 1/N \sum_{i=1}^{N_t} \sum_{k=1,k\neq m}^{N} X_k^i \sum_{n=1}^{N} H_{n(k)}^{j,i} e^{j2\pi(m-k)n/N} + W_m^j \quad n = 1,2,...N \tag{II.7}$$

Therefore, the received signal can be expressed in the matrix format as shown below.

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{II.8}$$

where

$$\mathbf{y} = [\mathbf{y}_1^T, \mathbf{y}_2^T, ..., \mathbf{y}_N^T]^T, \mathbf{x} = [\mathbf{x}_1^T, \mathbf{x}_2^T, ..., \mathbf{x}_N^T]^T, \quad and \quad \mathbf{w} = [\mathbf{w}_1^T, \mathbf{w}_2^T, ..., \mathbf{w}_N^T]^T, \tag{II.9}$$

and

$$\mathbf{H} = \begin{bmatrix} \mathbf{H_{1,1}} & \mathbf{H_{1,2}} & \cdots & \mathbf{H_{1,N}} \\ \mathbf{H_{2,1}} & \mathbf{H_{2,2}} & \cdots & \mathbf{H_{2,N}} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H_{N,1}} & \mathbf{H_{N,2}} & \cdots & \mathbf{H_{N,N}} \end{bmatrix} \tag{II.10}$$

$$\mathbf{y_m} = \left[y_m^1, y_m^2, ..., y_m^{N_r},\right]^{\mathbf{T}} \mathbf{x_m} = \left[x_m^1, x_m^2, ..., x_m^{N_r},\right]^{\mathbf{T}} \quad \textbf{and} \quad \mathbf{w_m} = \left[w_m^1, w_m^2, ..., w_m^{N_r},\right]^{\mathbf{T}} \tag{II.11}$$

$$\mathbf{H_{n,m}} = \begin{bmatrix} H_{n,m}^{1,1} & H_{n,m}^{1,2} & \cdots & H_{n,m}^{1,N_t} \\ H_{n,m}^{2,1} & H_{n,m}^{2,2} & \cdots & H_{n,m}^{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n,m}^{N_r,1} & H_{n,m}^{N_r,2} & \cdots & H_{n,m}^{N_r,N_t} \end{bmatrix} \tag{II.12}$$

where each element is defined as

$$H^{j,i}_{n,m} = 1/N \sum_{n=1}^{N} H^{j,i}_{n,(m)} e^{-j2\pi n(m-k)/N} \quad \text{(II.13)}$$

2.3 ZF/MMSE Detector

One can Calculate ZF/MMSE Solution matrix for entire OFDM Symbol. Here we are calculating on each subcarrier q. Let the received signal on q^{th} subcarrier is

$$\mathbf{y}(q) = \mathbf{H}(q)\mathbf{x}(q) + \mathbf{w}(q) \quad \text{(II.14)}$$

where $\mathbf{H}(q)$ is $N_r \times N_t$ matrix on subcarrier q obtained after FFT of Channel Matrix.

ZF Solution:

we need to find a matrix $W(q)$ which satisfies $W(q)H(q) = I$. Zero Forcing (ZF) linear detector for meeting this constraint given by,

$$\mathbf{W}(q) = (\mathbf{H}^H(q)\mathbf{H}(q))^{-1}\mathbf{H}^H(q) \quad \text{(II.15)}$$

MMSE Solution:

The Minimum Mean Square Error (MMSE) approach tries to find a coefficient $\mathbf{W}(q)$ which minimizes the criterion, $\mathbf{E}[(\mathbf{W}(q)\mathbf{Y}(q) - \mathbf{X}(q))(\mathbf{W}(q)\mathbf{Y}(q) - \mathbf{X}(q))^H]$ solving,

$$\mathbf{W}(q) = (\mathbf{H}^H(q)\mathbf{H}(q) + \mathbf{N}_0\mathbf{I})^{-1}\mathbf{H}^H(q) \quad \text{(II.16)}$$

2.4 Simulation Results

We first studied the performance and comparison of different modulation schemes (4QAM,16QAM,64QAM and 256QAM) with ZF and MMSE detection methods for MIMO OFDM system. A MIMO-OFDM combination using MRC at the receive end was then investigated in a Rayleigh multipath environment. We try to achieve maximum gain by sending copies of the same OFDM through a $N_t \times N_r$ MIMO System. This is also called transmit diversity in OFDM systems. Maximum Ratio Combining was then used to boost the received estimated signal. Different configurations of the parameters in the 802.11n and 802.11ac standards were investigated to examine the effect on the received BER values.

Figure II.3: MQAM BER Plots for 2×2 20MHz

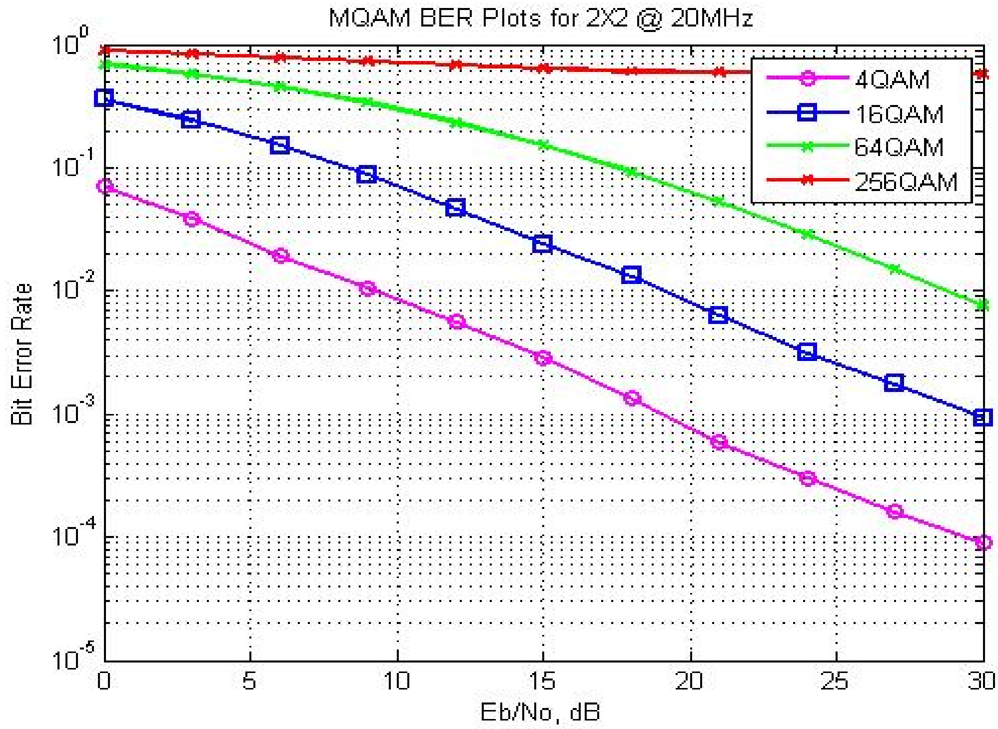


Figure II.4: MQAM BER Plots for 2×2 40MHz

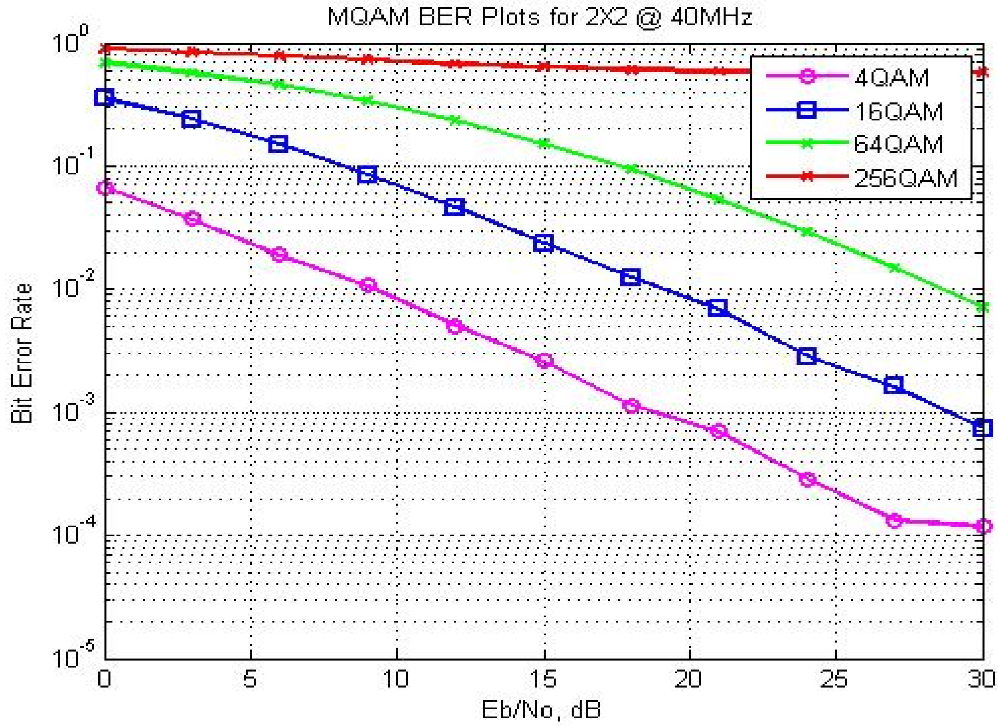


Figure II.5: BER Plots for 4×4 40MHz with ZF/MMSE

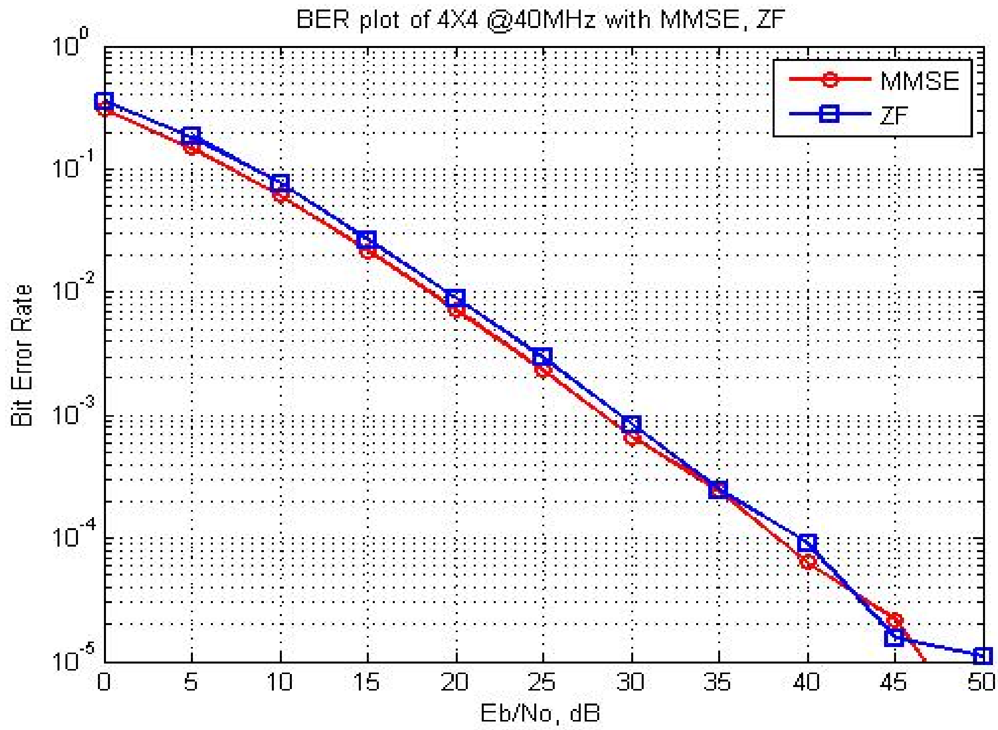


Figure II.6: BER Plots for 4×4 80MHz with ZF/MMSE

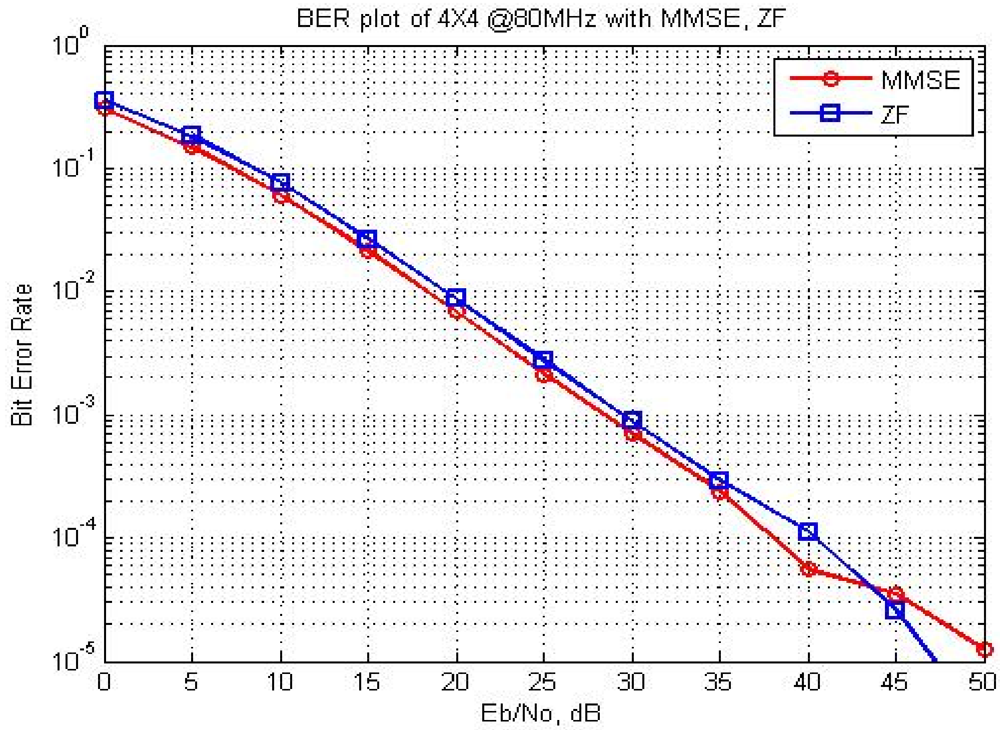


Figure II.7: logyplot: BER Plots for 4×4 80MHz with ZF/MMSE

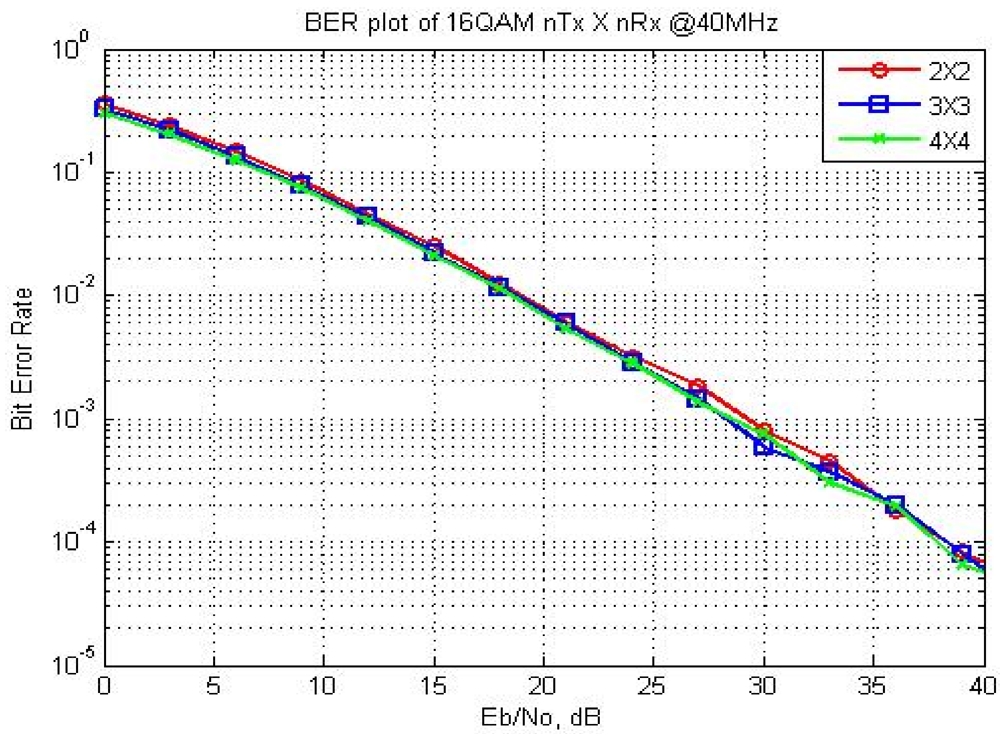
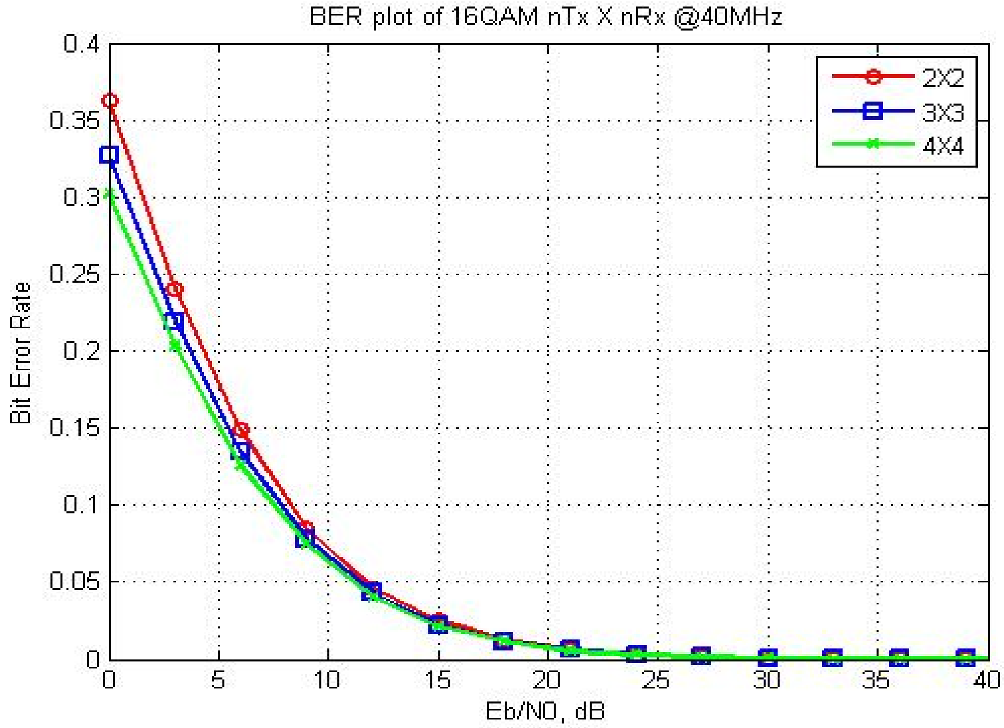


Figure II.8: linear plot: BER Plots for 4×4 80MHz with ZF/MMSE



2.5 Conclusions

[htbp] The choice of modulation scheme depends on the scenario with respect to the factors of transmission required.For instance, 16QAM transmit more symbols than 4QAM. The $N_t \times N_r$ MIMO System, four desirable attributes usually compete with one another. For example, an increase in data rate will often require an increase in either the error rate or transmit power. estimated BER with receiver architecture based on ZF and MMSE receiver. As expected, due to increasing the total number of transmitted symbols per second, there would be an increase in the total number of errors and therefore one need to operate at a higher SNR values.

Part III

MU-MIMO OFDM With Zero-Forcing Beamforming

CHAPTER III

MU-MIMO OFDM With ZF/MMSE Zero-Forcing Beamforming

1 Introduction

In MU-MIMO more than one user can be served in the same bandwidth using appropriate precoders at BS. This technique is just like SU-MIMO where one or more streams transmitted at a time using multiple antennas belonging to the same user. In MU-MIMO each stream could belong to a different user i.e., instead of stream multiplexing, MU-MIMO does user multiplexing. For scenarios where large number of users is to be served in one cell or to serve a limited number of users with increased throughput, MU-MIMO can be used.

In the previous chapter *MU-MIMO OFDM With ZF/MMSE Zero-Forcing Beamforming*. we have discussed about SU-MIMO System. In this chapter, we investigate a $N \times M$ MU-MIMO downlink systems under Rayleigh adding channel using different modulation techniques. First MU-MIMO System Model is described. This MU-MIMO system is then combined with an OFDM signal with parameters specified in IEEE 802.11ac standard. The results obtained from MATLAB simulation in a Rayleigh multipath environment were discussed.
The three gains that are useful in increasing the performance of MU-MIMO systems are defined as follows.

1.1 Spatial Diversity Gain

This is the technique for improving communication quality by transmitting and receiving with multiple antennas. Each pair of transmit and receive antennas provides a signal path by sending signals that carry the same information through different paths. Hence multiple independently faded replicas of the data symbol can be obtained and more reliable reception is achieved.

1.2 Spatial Multiplexing Gain

This is the performance improvement derived from using multiple antennas to transmit multiple signal flows through space in parallel. For a MIMO system with N_t transmitting antennas and N_r receiving antennas, the maximum achievable spatial multiplexing gain is minimum of N_t and N_r .

1.3 Multi-User Diversity Gain

MU-MIMO offers additional degrees of freedom when compared to SU-MIMO since multiple users are multiplexed in the same physical channel. This can be achieved by pairing users whose precoders are orthogonal to each other in a data-region and then precoding them appropriately so that each user sees only its own information which means cancelling IUI. The main advantages that lead to MIMO shift to MU-MIMO from SU-MIMO communications are:

1. MU-MIMO schemes allow for direct gain in multiple-access capacity (proportional to number of transmit antennas) because of multiplexing of data of several users in the same radio channel.
2. MU-MIMO schemes are more immune to loss of channel rank because of line of sight (LOS) conditions or antenna correlation, which is a major problem that causes performance degradation in SU-MIMO communications.

2 Challenges of MU-MIMO

MU-MIMO has tremendous benefits which are achieved by overcoming some challenges. Multiple users using the same resources at the same time would lead to several issues that need to be considered, some of them are mentioned here.

2.1 Interference

When multiple users are using the same resources at the same time, there would be severe interference between their signals. Each user should be capable of decoding his respective stream by reducing the interference due to other stream. This can be achieved by careful pre-processing at the transmitter and post-processing at the receiver.

2.2 post-processing

n single-user transmission, MIMO could be used for spatial multiplexing, where multiple symbols are transmitted to the same user. For example, consider a 2×2 single-user system, in which the received vector can be represented as

$$y = Hx + w \tag{III.1}$$

where the transmitted vector x(2×1) represents 2 symbols that are transmitted simultaneously to a particular user, thus doubling the user throughput. In order to decode the 2 symbols from the received vector y(2×1), a simple approach would be to build a linear receiver that diagonalises the system, i.e., multiply the received vector y by H^{-1}.

In the MU-MIMO case, the effective received vector y, is a concatenation of the symbols received by geographically separated users, and post processing must be done in such a way to reduce the interference from the other user. Several receiver configurations such as MMSE, maximum ratio combining (MRC) and ZF are possible but MMSE receiver is shown to reduce the interference effectively.

2.3 Precoding/Pre-processing

Because of this limitation on the interference cancellation that can be done at the MS, good precoders need to be designed, such that we beamform efficiently towards the two users. However this would require good knowledge of the channels to both users at the BS, which requires heavy amounts of feedback. So we would need to come up with the best possible precoders to use at the BS, with a limitation on the feedback rate.

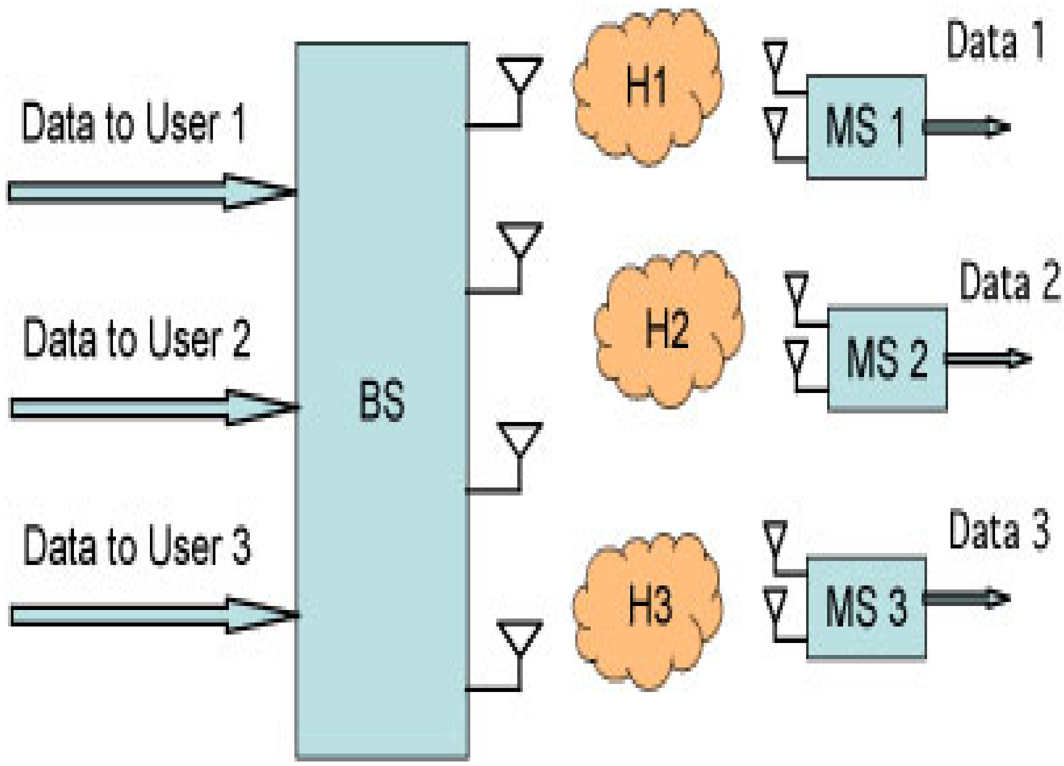
3 ZF Beamforming Precoding Technique and MIMO detection for MU-MIMO OFDM

The main benefit of ZF Beamforming scheme is that the interference is pre cancelled at the transmitter side.

3.1 System Model

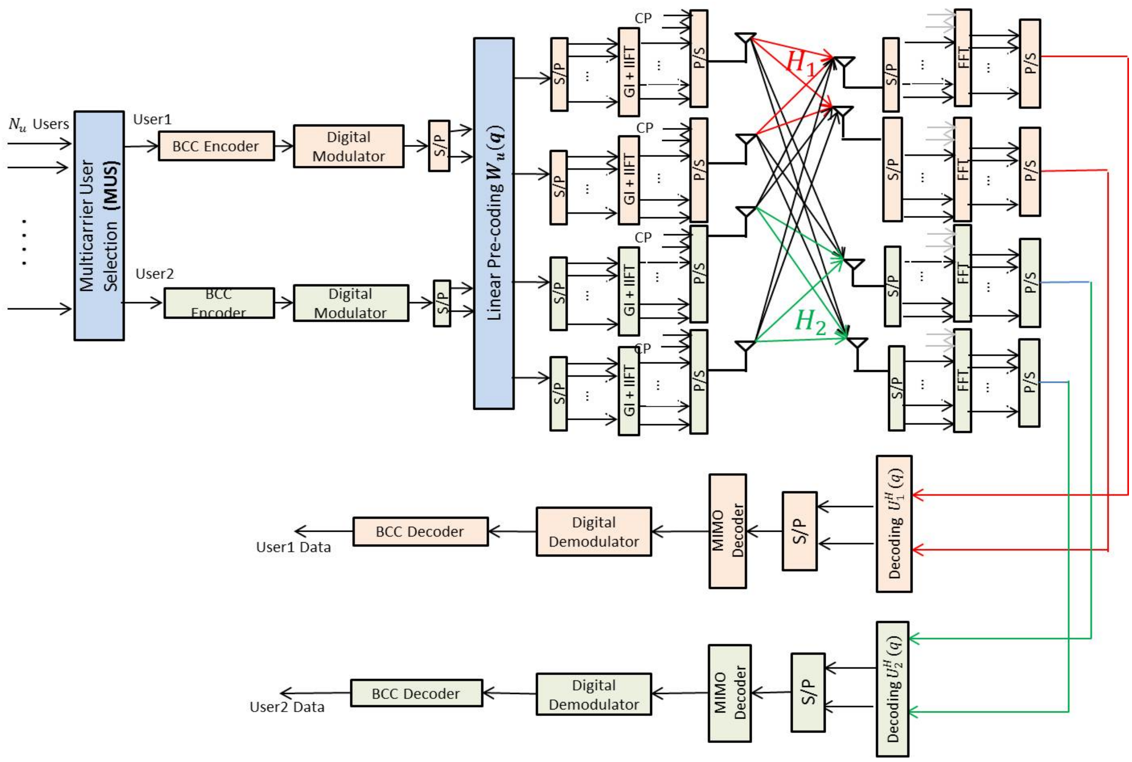
We consider a single-cell MU downlink system with N_t transmit antennas at the base station(BS) and N_u mobile users each equipped with N_r receive antennas. The system operates with N_c OFDM subcarriers, N_d of which are used to transmit user data while the rest correspond to pilots and guard bands(zero carriers). Transmitter and Receiver both knows the Channel state information(CSI). For simplicity, consider 4×2^2 System. ($N_T = 4$, $N_u = 2$ and $N_R = 2$).

Figure III.1: MU-MIMO System Model



As shown in Figure III.2, the information bits for each user u are encoded using a separate convolution encoder. The resulting coded bits are then punctured, interleaved and mapped onto modulation symbols from an M-ary modulation alphabet. ZF Beamforming linear precoding is applied to the each user symbols before being processed by a conventional OFDM modulator made of an IFFT stage and the addition of a guard interval(GI). This transmitter scheme uses the parameters specified in IEEE 802.11 ac standards[1]. Let $\mathbf{H}_u(q) \in \mathbb{C}^{N_r \times N_t}$ represents the channel gain matrix corresponding to the u^{th} user over q^{th} subcarrier.

Figure III.2: Block Diagram of MU-MIMO OFDM



admitting SVD

$$\mathbf{H}_u(q) = \mathbf{U}_u(q)\mathbf{\Sigma}_u(q)\mathbf{V}_u^H(q) \tag{III.2}$$

where $\mathbf{V}_u(q) = \left[\mathbf{v}_{u,1}(q), \mathbf{v}_{u,2}(q), ..., \mathbf{v}_{u,N_t}(q)\right] \in \mathbb{C}^{N_t \times N_t}$
$\mathbf{U}_u(q) = \left[\mathbf{u}_{u,1}(q), \mathbf{u}_{u,2}(q), ..., \mathbf{u}_{u,N_r}(q)\right] \in \mathbb{C}^{N_r \times N_r}$ are right and left singular unitary matrices.$\mathbf{\Sigma}_u(q) = \left[\sigma_{u,1}(q), \sigma_{u,2}(q), ..., \sigma_{u,N_r}(q)\right] \in \mathbb{R}^{N_r \times N_t}$
therefore, after postprocessing, $\tilde{\mathbf{H}}_u(q)$ the equivalent channel gain matrix of user u on subcarrier q can be represented as

$$\tilde{\mathbf{H}}_u(q) = \mathbf{U}_u^H(q)\mathbf{H}_u(q) = \mathbf{\Sigma}_u(q)\mathbf{V}_u^H(q) \tag{III.3}$$

Now,

$$\tilde{\mathbf{H}}_u(q) = \begin{bmatrix} \tilde{\mathbf{h}}_{u,1}(q) \\ \tilde{\mathbf{h}}_{u,2}(q) \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_2 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \mathbf{v}_{u,1}^H(q) \\ \mathbf{v}_{u,2}^H(q) \\ \mathbf{v}_{u,3}^H(q) \\ \mathbf{v}_{u,4}^H(q) \end{bmatrix} \tag{III.4}$$

Therefore the availability of CSI at the transmitter allows to convert every user's channel, on every subcarrier q, into N_r parallel spatial channels.

Now, Assuming perfect frequency synchronization between transmitter and receiver and a cyclic prefix duration exceeding the channel delay spread, the received signal at the k^{th} virtual user on subcarrier q for an arbitrary OFDM symbol may be written as

$$\tilde{y}_k(q) = \tilde{\mathbf{h}}_k(q)\mathbf{X}(q) + \tilde{w}_k(q) \quad k \in 1, ..., N_u N_r \tag{III.5}$$

where k is the index of the virtual user corresponding to the n^{th} receive antenna of the u^{th} original user. and $\tilde{\mathbf{h}}_{\mathbf{k}}(\mathbf{q}) = \tilde{\mathbf{h}}_{\mathbf{u,1}}(\mathbf{q}) = \sigma_{\mathbf{1}}\mathbf{v}^{\mathbf{H}}_{\mathbf{u,1}}(\mathbf{q}) \in \mathbb{C}^{\mathbf{1}\times\mathbf{N_t}}$ is channel coefficient of virtual user k and

$$\tilde{\mathbf{w}}_k(q) = \mathbf{U}^H_{u,1}(q)\mathbf{w}_k(q) \quad \sim \mathcal{CN}(0, \sigma_n^2) \tag{III.6}$$

Let $\tilde{\mathbf{H}}_{\mathcal{U}}(q)$ with size $\mathcal{U} \times N_t$ be the matrix collection of channel coefficients for the selected virtual users on subcarrier q. and $\mathcal{U}$ is total no. of virtual users

$$\tilde{\mathbf{H}}_{\mathcal{U}}(q) = [\tilde{\mathbf{h}}^T_{u_1}(q), \tilde{\mathbf{h}}^T_{u_2}(q), ..., \tilde{\mathbf{h}}^T_{u_{\mathcal{U}}}(q)]^T \tag{III.7}$$

Assuming a linear precoder $\mathbf{W}_{\mathcal{U}}(q)$ is used, The transmitted symbol vector $\mathbf{X}(q)$ is

$$\mathbf{X}(\mathbf{q}) = \mathbf{W}_{\mathcal{U}}(q)\mathbf{s}_{\mathcal{U}}(q) \tag{III.8}$$

where $\mathbf{W}_{\mathcal{U}}(q) = \left[\mathbf{W}_{u_1}(q)...\mathbf{W}_{u_{\mathcal{U}}}(q)\right]$ is $N_T \times \mathcal{U}$ precoding matrix. and $\mathbf{s}_{\mathcal{U}}(q) = \left[\mathbf{s}_{u_1}(q)...\mathbf{s}_{u_{\mathcal{U}}}(q)^T\right]$ is $\mathcal{U} \times 1$ vector containing the information symbols belonging to the selected virtual users. as shown in Figure III.3, $\mathbf{W}_{\mathcal{U}}(q)$ must be chosen by ZF-Beamforming scheme such that it cancels out IUI and i.e

$$\tilde{\mathbf{H}}_{\mathcal{U}}(q)\mathbf{W}_{\mathcal{U}}(q) = \mathbf{I}_{\mathcal{U}} \tag{III.9}$$

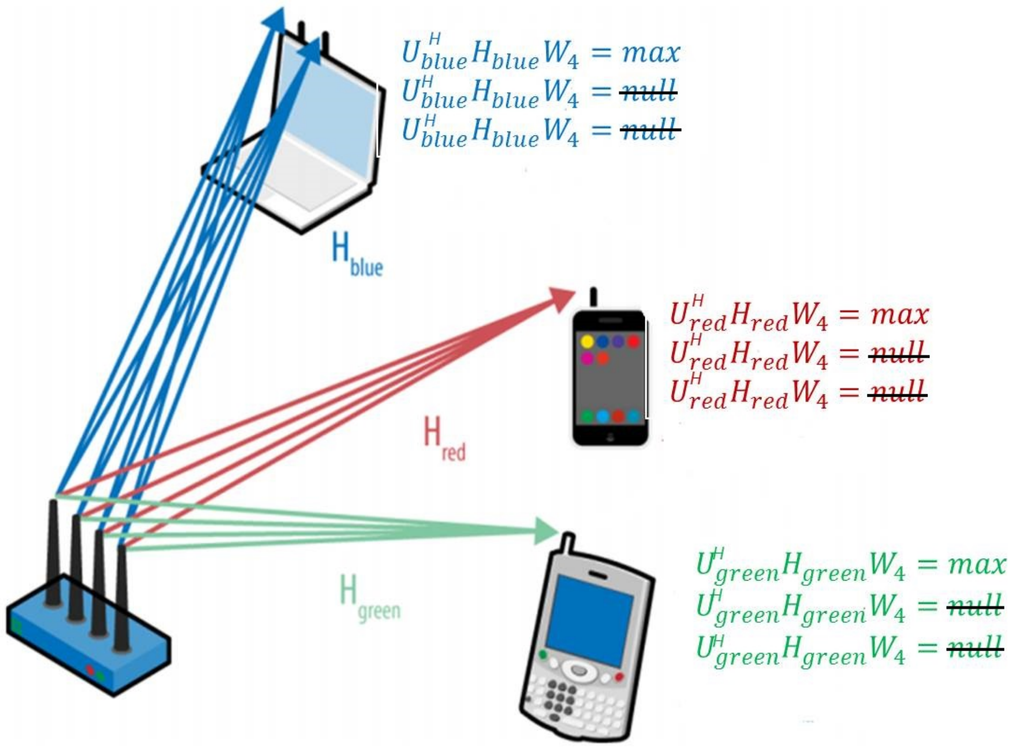
Condition for the solution $\mathbf{W}_{\mathcal{U}}$ to exist is $\mathbf{N_t} \geq \mathcal{U}$. and solution that gives zero-IUI is the pseudo-inverse of $\tilde{\mathbf{H}}_{\mathcal{U}}(q)$ is:

$$\mathbf{W}_{\mathcal{U}} = \tilde{\mathbf{H}}^H_{\mathcal{U}}(q)(\tilde{\mathbf{H}}_{\mathcal{U}}(q)\tilde{\mathbf{H}}^H_{\mathcal{U}}(q))^{-1} \tag{III.10}$$

The received signal(III.5) at k^{th} virtual user on q^{th} subcarrier becomes

$$\tilde{y}_k(q) = s_k(q) + \tilde{n}_k(q) \tag{III.11}$$

Figure III.3: Beamforming example



which can be decoded easily.

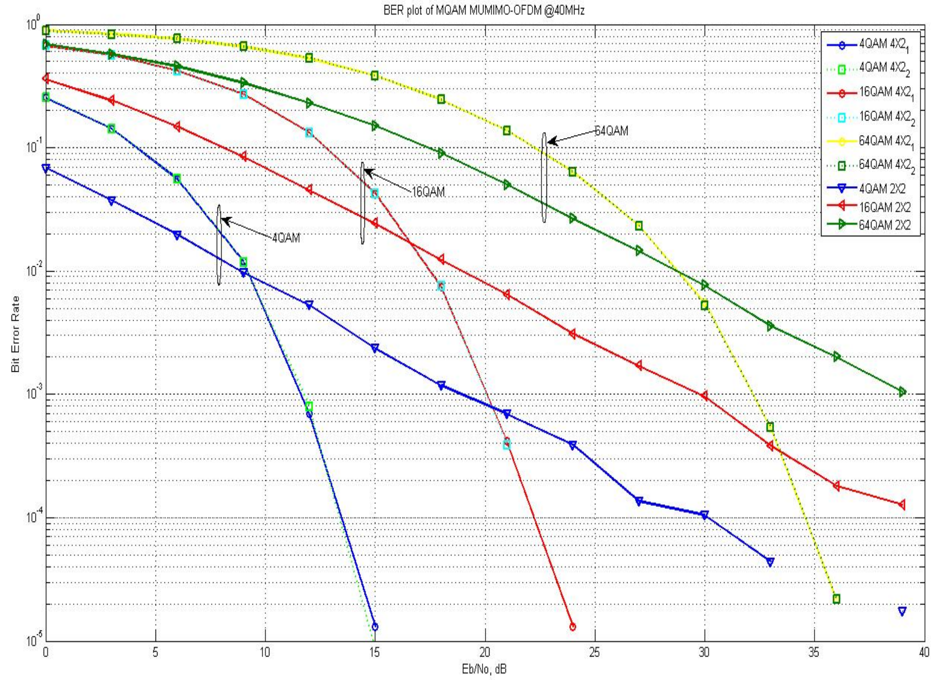
3.2 Simulation Results

We first studied the performance and comparison of different modulation schemes (4QAM,16QAM,64QAM and 256QAM) with ZF Beamforming technique for MU-MIMO OFDM system. Different configurations of the parameters in the 802.11n and 802.11ac standards were investigated to examine the effect on the received BER values.

3.3 Conclusions

MU-MIMO is a promising technique which allows more than one user that can be served in each subcarrier. A ZF-Beamforming technique for MU-MIMO has been proposed for the IEEE 802.11ac wireless standard. Optimum number of users can be served simultaniously is equal to minimum number of antennas at the base station and the mobile station. The choice of modulation scheme depends on the scenario with respect to

Figure III.4: BER Plots MQAM MU-MIMO OFDM@ 40MHz



the factors of transmission required.

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