Design And Implementation of Massive MIMO With F-Domain Equalization

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Abstract- *With the need for increased data rates in wireless networks, key enablers of high data rate transmission are being sought. Massive Multiple Input Multiple Output (MIMO) systems have emerged as one of such promising techniques which can address the requirement. However, due to frequency selective nature of wireless channels and different variants of channel conditions, systems employing massive MIMO encounter degraded Bit Error Rate (BER) performance. In this paper, a massive MIMO system has been designed and has been employed to commonly existing diverse channel conditions. Space Time Block Coding (STBC) has been used to implement the MIMO system practically. To mitigate the issue of degraded BER, channel equalization has also been implemented in conjugation with MIMO. The performance of the system has been evaluated in terms of the Bit Error Rate and Spectral Efficiency of the system. Different channel models have considered to emulate practical wireless channel conditions.*

Keywords- Multiple Input Multiple Output (MIMO), Zero Forcing Equalizer, Space Time Block Coding (STBC), Bit Error Rate (BER), Spectral Efficiency.

I. INTRODUCTION

The contemporary wireless communication scenario is facing the challenge of increased data rates due to the rampant sharing of multimedia data. With the channel bandwidth being limited, increasing the bandwidth or spectral efficiency of the system is a promising aspect [1]-[2]. Multiple Input Multiple Output (MIMO) systems are once such avenue [3]. MIMO systems increase the channel capacity manifold compared to Single Input Single Output (SISO) systems thereby enabling higher data rate transmission for the same bandwidth. The schematic for a typical MIMO system is depicted in figure 1.

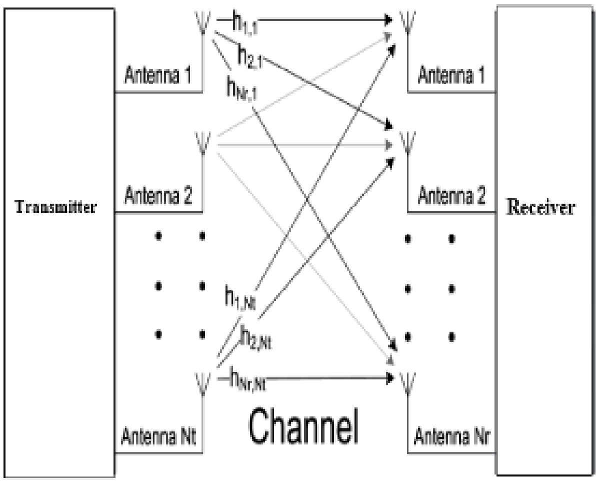

Fig.1. Conceptual model of a MIMO system

The MIMO based system has multiple transmitter and multiple receivers which create parallel data paths for transmission and reception which in tem allows enhanced data rates for the same limited bandwidth [4]. To implement this MIMO based transmission scheme practically, Space Time Block Coding (STBC) is often employed in which the data stream is arranged as a matrix with the number of columns equating to the number of MIMO transmitters and the number of rows equating to the number of time slots of transmission. The symbols of STBC transmission can be estimated as:

$$H^{+} = (H^{H}H)^{-1}H^{H} \quad (1)$$

Here,
H^{+} represents the Moore-Penrose pseudo inverse since the channel matrix,
H is the channel matrix and it may not always be square for the STBC matrix. Typically, the channel capacity is enhanced as per the following relation:

$$C = f\{kB\text{1pg}_2\left[1 + \frac{h_{ij}^2 S}{N}\right]\} \quad (2)$$

Here,
C is the channel capacity
B is the channel bandwidth
S is the signal power
N is the noise power
k is a constant depending on system parameters
f is a function depending on system parameters
h is the MIMO channel matrix
i is the number of transmitters
j is the number of receivers

From equation 2, it can be inferred that as the number of transmitters and receivers increase, the channel capacity also increases. However, this also increases the complexity of the decoding process [5]. The most ubiquitous multiplexing technique which is used in conjugation with MIMO systems is the orthogonal frequency division multiplexing (OFDM) which renders relatively high spectral efficiency. The mathematical condition for the condition of orthogonality of 'n' subcarriers is given by:

$$\int_0^T x1(t).x2(t)x3(t)\ldots.xn(t)dt = 0 \qquad (3)$$

Here,
x1, x2 … xn are the different sub-carriers for OFDM transmission
n is the total number of carriers
T is the period of the carriers
The system comprising of MIMO-OFDM suffers from frequency selective nature of channels and thereby encounters degraded BER performance in general [6]-[7].

II. NATURE OF WIRELESS CHANNELS

A. Freqqeuncy Selective Nature

Typically, wireless channels depict frequency selective nature i.e. they behave differently for different frequencies. Moreover, the frequency selectivity is not fixed by also exhibits temporal variation [8]. This is illustrated in figure 2.

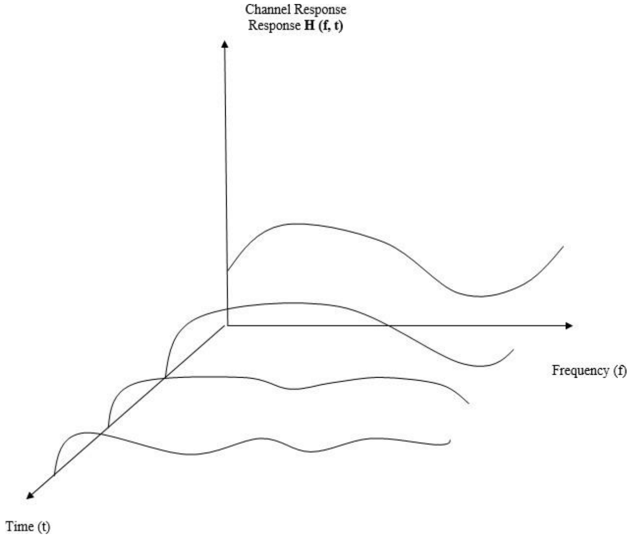

Fig. 2. Frequency Response of typical wireless channels

The composite impulse of the wireless channels corresponding to multi-path propagation effects can be given by:

$$h(t) = \sum_{i=1}^{n} h_n \qquad (4)$$

h(t) is the composite impulse response of the channel. h(n) corresponds to each of the responses to single tone frequencies.

To convert the impulse response of the channel into the time domain, we compute the Fourier Transform given by:

$$H(f) = \int_{-\infty}^{\infty} h(t)e^{-j\omega t}dt \qquad (5)$$

Here,
H(f) is the channel response in frequency domain
ω is the angular frequency
The sampled version of the channel response is given by:

$$H(f,nTs) = \sum_{i=1}^{n} H(f,t - nT_s) \qquad (6)$$

Here,
Ts is the sampling time for channel sounding
n is the number of samples
f is the frequency metric

For OFDM transmission, often to reduce the effects of frequency selectivity of channels, the cyclic prefix (CP) is inserted and is given by:

$$S_{CP} = S_n - S_{n-k} \qquad (7)$$

Here,
S_{CP} is the samples in the cyclic prefix
S is the original signal
n are the total number of samples
(n-k) are the samples which are appended as the cyclic prefix

B. *Need for Equalization*

Noise effects in case of wireless channels are inevitable and it becomes even more prominent with different paths of the MIMO system seeing a slightly different channel condition [9]-[10]. Thus it becomes necessary to mitigate the effects of such a frequency selective channel. It can be done by the design of an equalizer which tries to revert the effects of the channel. The design of the equalizer requires the information regarding the channel response h(f). Since any practical system can sense the channel in the discrete time domain, therefore the channel impulse response can be re-considered as h(n) [11]. Let the channel in the frequency domain be H(z). Then the output of the channel is:

$$y(n) = x_{(n)} * h(n) \tag{8}$$

$$Y_{(z)} = X_{(z)}.H(z) \tag{9}$$

Where, * stands for convolution
x(n) is the input to the channel
y(n) is the output of the channel
The aim at design of an equalizer is the design of a system with a transfer function

$$E(z) = \frac{1}{H(z)} \tag{10}$$

The equalizer is placed just before the receiver and its performance depends greatly upon the accuracy with which the channel is estimated in the first place [12].

III. PROPOSED SYSTEM

The proposed system implements the MIMO-OFDM system for four practical channel models which are the Additive White Gaussian Noise (AWGN), Nakagami, Rayleigh and Rician channel models. The different channel models emulate the different practical behavior of wireless channel [14]. The AWGN channel is characterized by constant noise power for all frequencies. In the Rayleigh channel, there is no line of sight (LOS) component, but only Multi Path Components (MPCs). In the Rician channel model, there is a strong LOS component and also multi path components. The Nakagami channel is basically a modified version of the Rician channel with group scattering of waves causing group delays at receiver. This causes interference between different wave clusters [15]. While there are different equalization techniques which can be employed, equalization used in the proposed system is the zero forcing equalization which owing to its relative simplicity of implementation can be incorporated with massive MIMO systems [16]. The mathematical formulation for the block linear equalizer (BLE) with zero forcing (ZF) approach is mathematically is given by:

$$\hat{d}_{c,\ ZF\text{-}BLE} = (A^H R_n^{-1} A)^{-1} A^H R_n^{-1} e \tag{11}$$

Or,

$$\hat{d}_{c,\ ZF\text{-}BLE} = d + (A^H R_n^{-1} A)^{-1} A^H R_n^{-1} n \tag{12}$$

Here,
$\hat{d}_{c,\ ZF\text{-}BLE}$ represents the zero forcing term
d are the desired symbols
$(A^H R_n^{-1} A)^{-1} A^H R_n^{-1} n$ is the residual noise term
H is the MIMO channel response
R_n is the Choleski decomposition of a conventional matched filter at the receiver
$A^H R_n^{-1}$ is the response of a typical whitening matched filter.
The SNR per symbol at the output of the ZF-BLE is given by:

$$\gamma_{ZF-BLE}(k,n) = \frac{E\{|d_n^k|^2\}}{(A^H R_n^{-1} A)^{-1}_{i,j}} \qquad (13)$$

Here,
E is the expectation of average value of the random variable
n is the symbol number
k is the number of samples

Considering correctness at the output of the ZFE, the output is given by [17]:

$$\gamma_{ZF-BLE}(k,n) = E\{|d_n^k|^2\}|\Sigma|^2_{i,j} \qquad (14)$$

Here, the errors in channel estimation can be minimized by employing the following relation:

$$E_h = \mathrm{mean}\{e^2[n]\} \to 0 \qquad (15)$$

Here,
E_h denotes the error in estimation
e denotes current error sample value
n denotes the number of error samples
The zero forcing equalizer tries to force the mean square error (mse) of the channel estimation to zero.
Mathematically, equalization is performed if,

$$x(k) = [0_M \quad I_M]\begin{bmatrix} u(k-1) \\ u(k) \end{bmatrix} + E\frac{W_M}{\sqrt{M}} Z_r r(k) \qquad (16)$$

Here,
MxM is the matrix size
u is the received signal
x is the recovered or equalized signal
W are the weights of the equalizer
E is the expectation or average value

IV. SIMULATION RESULTS

The system has been designed and simulated for OFDM transmission and MIMO-OFDM transmission for four different channel conditions which are:

1) AWGN
2) Nakagami
3) Rayleigh
4) Rcician

The performance of the proposed system is evaluated in terms of two performance metrics which are the bit error rate (BER) and spectral efficiency of the system.

The BER-SNR values for the different channel conditions are listed in Table I. The BER values are a measure of the Quality of Service (QoS) of the system.

TABLE I
BER ANALYSIS OF MIMO-OFDM SYSTEMS FOR DIFFERENT CHANNELS

S.No.	**BER**	**SNR Range**	**Case**
1.	10-1	4dB	OFDM-AWGN
2.	10-1	0.5dB	MIMO-OFDM-AWGN
3.	10--1	9dB	OFDM-Nakagami
4.	10-1	0.5dB	MIMO-OFDM-Nakagani
5.	10-1	10dB	OFDM-Rayleigh
6.	10--1	0.5dB	MIMO-OFDM-Rayleigh
7.	10-1	9dB	OFDM-Rician
8.	10-1	1dB	MIMO-OFDM-Rician
9.	10-2	4.5dB	OFDM-AWGN
10.	10-2	1dB	MIMO-OFDM-AWGN
11.	10--2	15.8dB	OFDM-Nakagami
12.	10-2	6dB	MIMO-OFDM-Nakagani
13.	10-2	14.9dB	OFDM-Rayleigh
14.	10-2	6dB	MIMO-OFDM-Rayleigh
15.	10-2	15dB	OFDM-Rician
16.	10--2	6dB	MIMO-OFDM-Rician
17.	10-3	7dB	OFDM-AWGN
18.	10-3	6dB	MIMO-OFDM-AWGN
19.	10-3	N.A.	OFDM-Nakagami
20.	10-3	8dB	MIMO-OFDM-Nakagani
21.	10--3	N.A.	OFDM-Rayleigh
22.	10-3	8dB	MIMO-OFDM-Rayleigh
23.	10-3	N.A.	OFDM-Rician
24.	10-3	8.5dB	MIMO-OFDM-Rician
25.	10-4	8dB	OFDM-AWGN
26.	10--4	8dB	MIMO-OFDM-AWGN
27.	10-4	N.A.	OFDM-Nakagami
28.	10-4	9.5dB	MIMO-OFDM-Nakagani
29.	10-4	N.A.	OFDM-Rayleigh
30.	10--4	10.1dB	MIMO-OFDM-Rayleigh
31.	10-4	N.A.	OFDM-Rician

32.	10-4	10dB	MIMO-OFDM-Rician

The values for the spectral efficiency in Bits/s/Hz for the four different channel conditions are listed in Table II. The spectral efficiency is a metric which is indicative of the channel capacity and spectral efficiency of the system.

TABLE II
ANALYSIS OF SPECTRAL EFFICIENCY FOR DIFFERENT CHANNELS

S. No.	**SNR**	**Spectral Efficiency**	**Channel Condition**
1.	2dB	1.92	AWGN
2.	2dB	1.89	Nakagami
3.	2dB	1.88	Rayleigh
4.	2dB	1.84	Rician
5.	4dB	1.97	AWGN
6.	4dB	1.95	Nakagami
7.	4dB	1.94	Rayleigh
8.	4dB	1.88	Rician
9.	6dB	1.98	AWGN
10.	6dB	1.96	Nakagami
11.	6dB	1.96	Rayleigh
12.	6dB	1.91	Rician
13.	8dB	2.0	AWGN
14.	8dB	1.98	Nakagami
15.	8dB	1.975	Rayleigh
16.	8dB	1.92	Rician
17.	10dB	2.0	AWGN
18.	10dB	1.98	Nakagami
19.	10dB	1.975	Rayleigh
20.	10dB	1.92	Rician

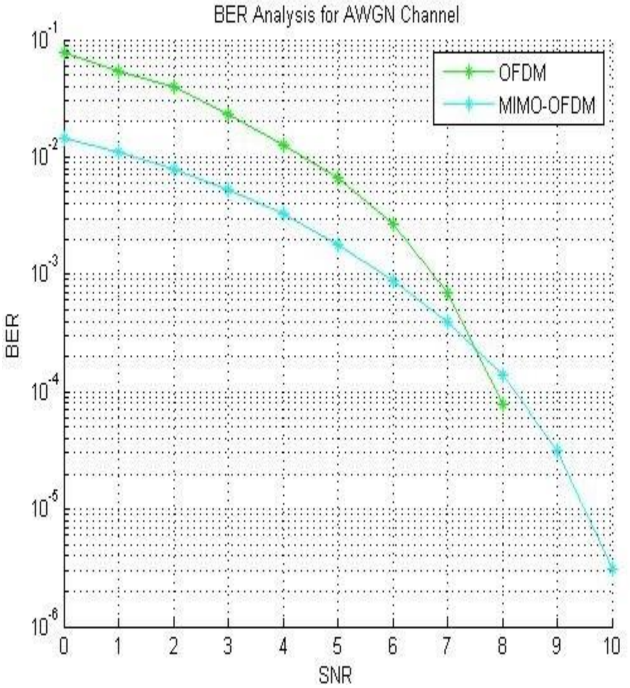

Fig. 3. BER Analysis for AWGN channel

Figure 3 depicts the BER curves for OFDM and MIMO- OFDM over AWGN channel conditions

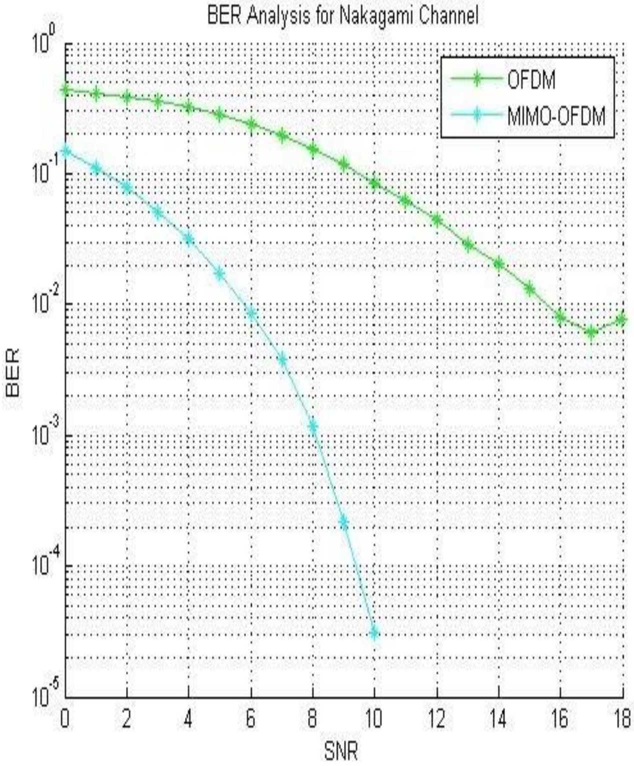

Fig. 4. BER Analysis for Nakagami channel

Figure 4 depicts the BER curves for OFDM and MIMO- OFDM over Nakagami channel conditions.

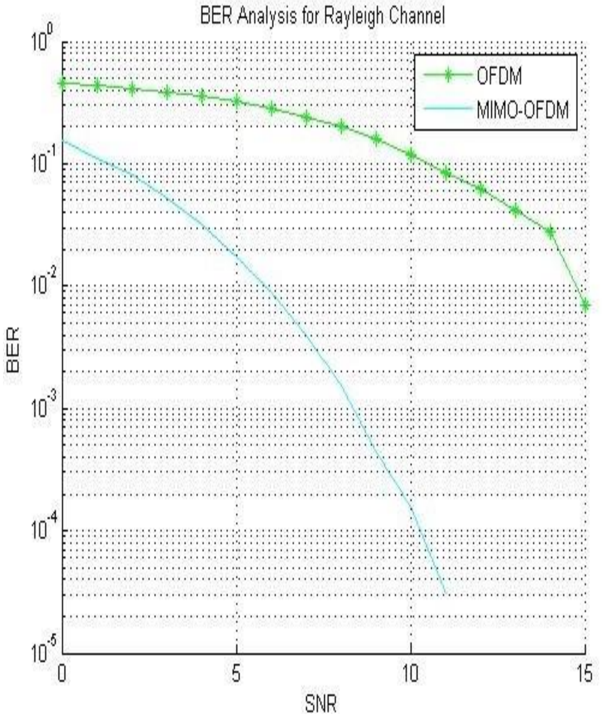

Fig. 5. BER Analysis for Rayleigh channel

Figure 5 depicts the BER curves for OFDM and MIMO- OFDM over Rayleigh channel conditions.

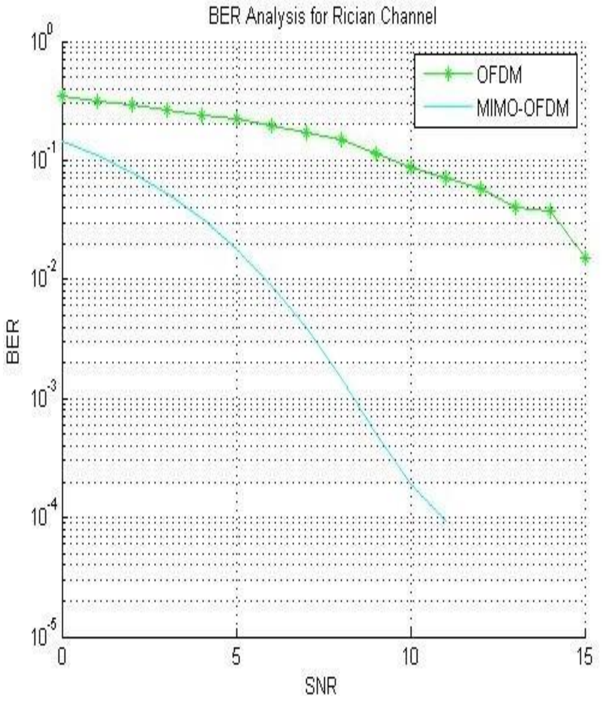

Fig. 6. BER Analysis for Rician channel

Figure 6 depicts the BER curves for OFDM and MIMO- OFDM over Rician channel conditions.

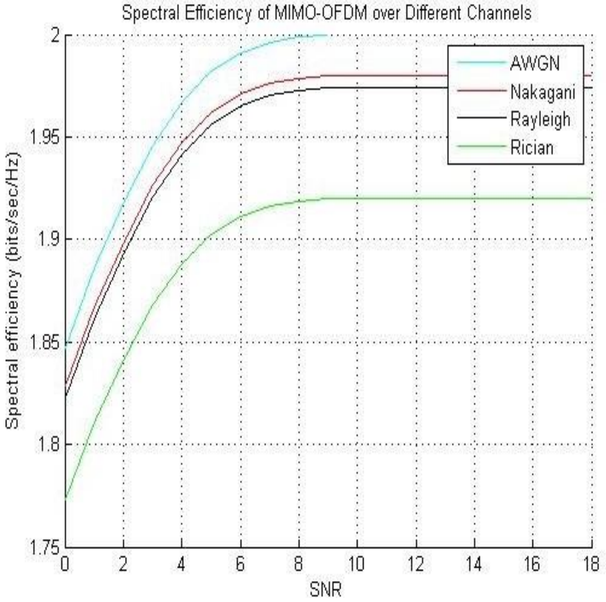

Fig. 7. Spectral Efficiency of proposed system over different channel conditions

Figure 7 depicts the spectral efficiency of the system, for the four channel conditions analyzed. The spectral efficiency of any system is a measure of the amount of data that can be transmitted as a function of the signal to noise ratio of the system. Typically, the spectral efficiency of the system increases monotonically with respect to the signal to noise ratio up to a point after which the increase saturates. The spectral efficiency bears coherence with the results of the BER performance of the system in the sense that the system with the least BER would exhibit the maximum spectral efficiency. This is so because the system which attains the least BER apparently can transmit more data without errors through the channel. This is also indicative of the actual channel capacity of the channel in terms of the error free data transmission. As the BER increases though, the spectral efficiency starts plummeting indicating the saturation of the channel capacity to force more bites per unit of the channel bandwidth available to the system.

V. CONCLUSION

It can be concluded from the previous discussions that MIMO systems can be considered to be key enablers in high data rate wireless communications. In the proposed approach, a comparative analysis of OFDM transmission and a combination of OFDM and MIMO has been done. The results indicate that the BER performance of the MIMO-OFDM system is better compared to the individual OFDM based transmission scheme. This tends to imply that the spectral efficiency of MIMO-OFDM is higher compared to conventional OFDM. The spectral efficiency of the proposed system is also evaluated to four channel conditions which are the AWGN, Nakagami, Rayleigh and Rician channel models which emulated practical wireless scenarios.

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