Journal of Network and Information Security
8 (1&2), 2020, 19-25
http://www.publishingindia.com/jnis

Performance Analysis of Zero Forcing and MMSE Equalizer on MIMO System in Wireless Channel

G. M. Waliullah[1], Diponkor Bala[2], Mst. Ashrafunnahar Hena[3], Md. Ibrahim Abdullah[4] and Mohammad Alamgir Hossain[5*]
[1,2,4]Department of Computer Science & Engineering, Islamic University, Kushtia, Bangladesh.
[3]Department of Electrical and Electronic Engineering, Islamic University, Kushtia, Bangladesh.
[5]Department of Computer Science & Engineering, Islamic University, Kushtia, Bangladesh.
Email: alamgirlovely@yahoo.com
*Corresponding Author

Abstract: In wireless communication research multiple communication antennas are one of the major contexts. At present wireless communication is moving fast and the best example is MIMO. Wireless transmission is suffering from fading and interference effects which may be combated with equalizer. As a result of fading and interference, it creates a problem for signal recovery in wireless communication. The MIMO system uses Multiple Transmit and Multiple Receive antennas which take advantages of multipath propagation during a high distraction environment. This paper analyses the performance of Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizer for 2×2 and 4×4 MIMO wireless channels. By using MATLAB toolbox version 2015a simulation results can be got to the RF processing lab. The Bit Error Rate (BER) features for various communication antennas is simulated in the MATLAB toolbox and many merits and demerits of the system are discussed. The simulation results show that the equalizer based zero-forcing receiver is helpful for noise-free channel and is successful in removing ISI, but MMSE is an optimal choice than ZF in terms of BER characteristics.

Keywords: ISI, Bit Error Rate (BER), BPSK, Maximal Ratio Combining (MRC), 2×2 MIMO channel, MIMO system, MMSE equalizer, Signal to Noise Ratio (SNR), ZF equalizer.

I. Introduction

Multiple Input Multiple Output (MIMO) refers to the antenna configuration technology for wireless communications where the multiple antennas are used at both transmitter and receiver sides. The antennas at both ends of the communications circuit are combined to reduce errors and optimize data speed [1] [2]. The MIMO system uses multiple antennas to transmit multiple parallel signals for transmission. The MIMO techniques have attracted great attention due to multiple antennas at both transmitter and receiver being employed; it provides the possibility of upper data rates compared to single antenna systems [3] [4]. A point-to-point (for single user) MIMO communication system promises large gains for both data transmission rates and reliability and these are accomplished via the utilization of space-time codes (diversity gain oriented) [5]. This technique grants higher channel capacity to wireless systems and is able to increase the capacity of the channel linearly with the numerous antennas and link range without additional bandwidth and power requirements [6].

In mobile communication systems, data transmission at high bit rates is important for several services like video, top-quality audio and mobile integrated service digital network. During the transmission of data at higher data transmission rates through the mobile radio channels, the channel impulse response can spread over many symbol periods as well as causes inter-symbol interference (ISI). This paper discusses the performances of ZF and MMSE equalization techniques by considering 2 transmitting and 2 receiving antenna cases (resulting in a 2×2 MIMO channel) and 4 transmitting and 4 receiving antenna cases (resulting in a 4x4 MIMO channel). For this study consider the flat fading Rayleigh multipath and BPSK modulation technique for the channel [7].

The ultimate goal is to provide universal personal and multimedia communication without reference to mobility or location with high data rates. The main purpose of a dynamic equalization is to compensate for the ISI. Equalizers are employed to reduce such interference. From the theoretical analysis of the MIMO system, it is clear that each transmit antenna transmits various signals so that the receiver can easily receive the transmitted signals. All signals are transmitted from all elements once and therefore the receiver solves a linear equation system to demodulate the message [8].

This paper is organized as follows: Section II explains the MIMO System. Section III explains the ZF Equalizer. Section IV explains the MMSE Equalizer. Section V is a Simulation Model. Section VI describes the Simulation Result and Discussion. And finally, the Conclusion is drawn in Section VII.

II. MIMO System

Multiple-Input Multiple-Output, abbreviated as MIMO, is a wireless technology that increases the data capacity of an RF radio by using multiple transmitting and receiving antennas as shown in Fig 1. In a MIMO system, the same data is transmitted through multiple antennas over the same path in the same bandwidth. Because of this, each signal reaches the receiving antenna through a different path, resulting in more reliable data. The data rate also increases by a factor determined by the number of transmit and receive antennas [9].

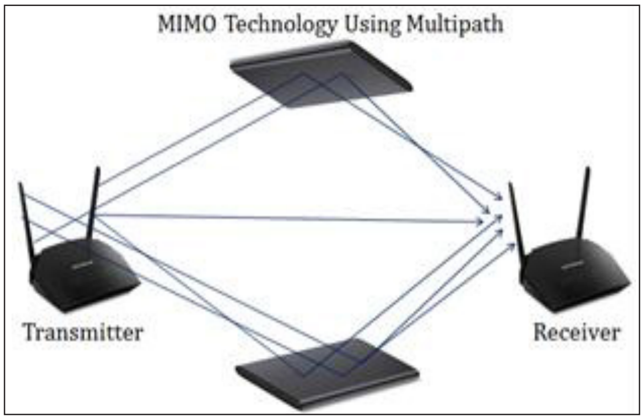

Fig. 1: MIMO Technology Using Multipath

Multipath is one of the parts of a MIMO technology that focuses on radio wave phenomena. Since the transmitted information is interrupted at different places such as bounces off walls, ceilings, and other objects, it receives the received signal at different times and different angles. At first, multipath involved interference and due to interference it gradually decreased wireless signals [10] [11].

MIMO takes advantages to increase receiver signal-capturing power, link reliability, performance and receiver diversity. Consequently, MIMO combines data streams arriving from different paths and at different times [11] [12].

More antennas usually equate to higher speeds. A wireless adapter with three antennas can have a speed of 600 Mbps. An adapter with two antennas has a speed of 300 Mbps. The router needs multiple antennas and must fully support all features of 802.11n to attain the highest speed possible.

A. 2×2 MIMO Channel

In a 2×2 MIMO channel shown in Fig. 2 probable usages of the available 2 transmitting antennas can be as follows:

- Consider that we have a transmission sequence, for example $\{x_1, x_2, x_3, \dots \dots \dots. x_n\}$.
- In normal transmission, we will be sending x_1 in the first time slot, x_2 in the second time slot, x_3 and so on.
- However, as we now have 2 transmitting antennas, we may group the symbols into groups of two. In the first time slot, send x_1 and x_2 from the first and second antenna. In the second time slot, send x_3 and x_4 from the first and second antenna, send x_5 and x_6 in the third time slot and so on.
- Notice that as we are grouping two symbols and sending them in the one-time slot, we need only n/2 time slots to complete the transmission. Hence the data rate is doubled.
- In the MIMO transmission scheme, this type of interpretation is very simple with 2 transmitting antennas and 2 receiving antennas.

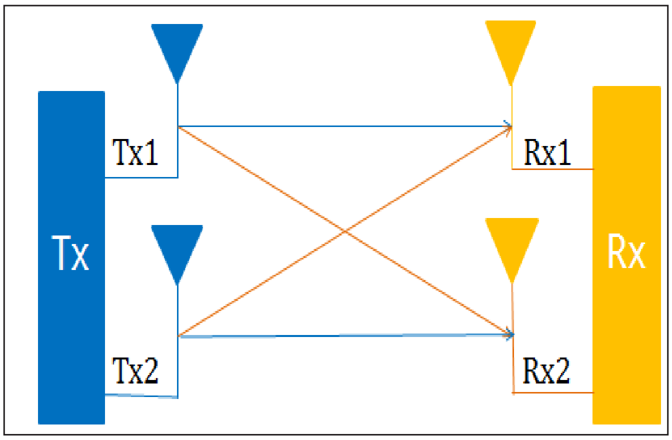

Fig. 2: 2 Transmit 2 Receive (2×2) MIMO Channel

III. Zero Forcing Equalizer

Zero Forcing equalizer is a method that applies inversely to the received signal so that it can restore the signal. It is one kind of graphical equalization algorithm that is widely used in communication systems. This form of equalizer was first proposed by Robert Lucky.

It has many useful applications. For example, by studying deeply of the MIMO system in 802.11n to know the accurate information about the channel at every antenna and two or more streams are recovered from the received signal. By applying the ZF equalizer technique it will be possible to put down the value of Inter Symbol Interference (ISI) at zero for a noise-free channel. This will be useful when ISI is significant compared to noise. The Zero Forcing Equalizer C(f) is represented by C(f) = 1/F (f) where f is a channel frequency response. The combination of channel and equalizer presents a flat frequency response and linear phase F(f)C(f) = 1[5] [13].

A. Zero Forcing (ZF) Equalizer for 2×2 MIMO Channel

Consider a 2×2 MIMO channel, the received signal on the first receive antenna is,

$$y_1 = h_{1,1}x_1 + h_{1,2}x_2 + n_1 = [h_{1,1}h_{1,2}]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_1 \quad (1)$$

The received signal on the second receive antenna is,

$$y_2 = h_{2,1}x_1 + h_{2,2}x_2 + n_2 = [h_{2,1}h_{2,2}]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_2 \quad (2)$$

where

y_1, y_2 are the received symbol on the first and second antenna respectively,

$h_{1,1}$ is the channel from 1st transmit antenna to 1st receive antenna,

$h_{1,2}$ is the channel from 2nd transmit antenna to 1st receive antenna,

$h_{2,1}$ is the channel from 1st transmit antenna to 2nd receive antenna,

$h_{2,2}$ is the channel from 2nd transmit antenna to 2nd receive antenna,

x_1, x_2 are the transmitted symbols and

n_1, n_2 is the noise on 1st, 2nd receive antennas.

The equation can be represented in matrix notation as follows:

$$\begin{bmatrix}y_1\\y_2\end{bmatrix} = \begin{bmatrix}h_{1,1} & h_{1,2}\\h_{2,1} & h_{2,2}\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}n_1\\n_2\end{bmatrix} \quad (3)$$

Equivalently,

$$Y = HX + N \quad (4)$$

Where,

Y = Received Symbol Matrix,

H = Channel Matrix,

X = Transmitted Symbol Matrix,

N = Noise Matrix.

To solve for x, we need to find a matrix W which satisfies WH = I. The Zero Forcing (ZF) detector for meeting this constraint is given by,

$$W = (H^H H)^{-1} H^H \quad (5)$$

Where

W - Equalization Matrix,

and H - Channel Matrix.

This matrix is known as the Pseudo inverse for a general m x n matrix where

$$H^H H = \begin{bmatrix}h_{1,1}^* & h_{2,1}^*\\h_{1,2}^* & h_{2,2}^*\end{bmatrix}\begin{bmatrix}h_{1,1} & h_{1,2}\\h_{2,1} & h_{2,2}\end{bmatrix}$$

$$= \begin{bmatrix}|h_{1,1}|^2 + |h_{2,1}|^2 & h_{1,1}^*h_{1,2} + h_{2,1}^*h_{2,2}\\h_{1,2}^*h_{1,1} + h_{2,2}^*h_{2,1} & |h_{1,2}|^2 + |h_{2,2}|^2\end{bmatrix} \quad (6)$$

B. BER with ZF Equalizer with 2×2 and 4×4 MIMO

Note that the off-diagonal terms in the matrix $H^H H$ are not zero. Since off-diagonal terms are not zero, the Zero Forcing Equalizer attempt to null out the interfering terms when carrying out the equalization, i.e. when solving for x_1 the interference from x_2 is tried to be nulled and vice versa. While doing so, there can be an amplification of noise. Hence Zero Forcing equalizer is not the best possible equalizer to do the job. However, it is simple and reasonably easy to implement. Further, it can be seen that, following zero-forcing equalization, the channel for symbol transmitted from each spatial dimension (space is an antenna) is a like a 1×1 Rayleigh fading channel. Hence the BER for 2×2 and 4×4 MIMO channel in Rayleigh fading with Zero Forcing equalization is similar to the BER obtained for a 1×1 channel in Rayleigh fading [14].

For BPSK modulation in Rayleigh fading channel, the bit error rate is derived as,

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{E_b}{N_o}}{\left(\frac{E_b}{N_o}\right)+1}}\right) \quad (7)$$

Where

P_b - Bit Error Rate

$\frac{E_b}{N_o}$ - Signal to Noise Ratio

IV. Minimum Mean Square Error Equalizer

A Minimum Mean Square Error (MMSE) is a conventional way that calculates the Mean Square Error (MSE) and tries to minimize the error. For this reason, it refers to the best common measure of estimator quality. The main property of MMSE is that it fails to remove all ISI perfectly but decreases the total power of the noise and ISI components in the output. Let x be an unknown random variable, and let y be a known random variable. An estimator x^ (y) is any function of the measurement y, and its mean square error is given by,

$$MSE = E\,\{(X^\wedge X^2)\} \quad (8)$$

Where the expectation is taken over both x and y.

By following the term AY + b we acquire a minimum MSE overall estimator and it is known as linear MMSE estimator. If the measurement Y is a random vector, A is a matrix and b is a vector.

A. Minimum Mean Square Error Equalizer for 2×2 MIMO Channel

Consider a 2×2 MIMO channel, the received signal on the first receive antenna is,

$$y_1 = h_{1,1}x_1 + h_{1,2}x_2 + n_1 = [h_{1,1}h_{1,2}]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_1 \tag{9}$$

The received signal on the second receive antenna is,

$$y_2 = h_{2,1}x_1 + h_{2,2}x_2 + n_2 = [h_{2,1}h_{2,2}]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n_2 \tag{10}$$

Where

y_1, y_2 are the received symbol on the first and second antenna respectively,

$h_{1,1}$ is the channel from 1st transmit antenna to 1st receive antenna,

$h_{1,2}$ is the channel from 2nd transmit antenna to 1st receive antenna,

$h_{2,1}$ is the channel from 1st transmit antenna to 2nd receive antenna,

$h_{2,2}$ is the channel from 2nd transmit antenna to 2nd receive antenna,

x_1, x_2 are the transmitted symbols and

n_1, n_2 is the noise on 1st, 2nd receive antennas.

The equation can be represented in matrix notation as follows:

$$\begin{bmatrix}y_1\\y_2\end{bmatrix} = \begin{bmatrix}h_{1,1} & h_{1,2}\\h_{2,1} & h_{2,2}\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}n_1\\n_2\end{bmatrix} \tag{11}$$

Equivalently,

$$Y = HX + N \tag{12}$$

Where,

Y = Received Symbol Matrix,

H = Channel Matrix,

X = Transmitted Symbol Matrix,

N = Noise Matrix.

The Minimum Mean Square Error **(**MMSE**)** approach tries to find a coefficient W which minimizes the criterion,

$$E\ \{[W_{y-x}]\ [W_{y-x}]H\} \tag{13}$$

Where

W - Equalization Matrix,

H - Channel Matrix,

n - Channel Noise and

y - Received signal.

To solve for x, we need to find a matrix W which satisfies $WH = I$. The Minimum Mean Square Error (MMSE) detector for meeting this constraint is given by,

$$W = [H^H H + N_o I]^{-1} H^H \tag{14}$$

This matrix is known as the Pseudo inverse for a general m x n matrix where

$$H^H H = \begin{bmatrix}h^*_{1,1} & h^*_{2,1}\\h^*_{1,2} & h^*_{2,2}\end{bmatrix}\begin{bmatrix}h_{1,1} & h_{1,2}\\h_{2,1} & h_{2,2}\end{bmatrix}$$

$$= \begin{bmatrix}|h_{1,1}|^2 + |h_{2,1}|^2 & h^*_{1,1}h_{1,2} + h^*_{2,1}h_{2,2}\\h^*_{1,2}h_{1,1} + h^*_{2,2}h_{2,1} & |h_{1,2}|^2 + |h_{2,2}|^2\end{bmatrix} \tag{15}$$

When comparing two equations i.e. eq. (5) and eq. (14) in Zero Forcing Equalizer, we see that both equations are comparable except N_oI. Actually, when the value of the noise term is zero, the MMSE equalizer minimizes to Zero Forcing equalizer.

V. Simulation Model

The following steps were taken to design the system.

- Generate a random binary sequence of +1′s and -1′s.
- Group them into pairs of two symbols and send two symbols in a one-time slot.
- White Gaussian noise is added after the multiplication of the symbols with the channel.
- Equalize the received symbols.
- To plot the simulation and theoretical results by repeating for multiple values.
- To plot the simulation and theoretical results by repeating for multiple values of $\frac{E_b}{N_o}$.

VI. Simulation Result and Discussion

A. Simulation Analysis for ZF

Let us discuss now the simulation results of ZF equalizer receiver BER performance characteristics. As expected, the simulated results with a 2×2 MIMO system using BPSK modulation in Rayleigh channel is showing matching results as obtained in for a 1×1 system for BPSK modulation in Rayleigh channel shown in Fig. 3. The ZF equalizer helps us to achieve the data rate gain. We might not be able to achieve the two fold data rate improvement in all channel conditions. It can so happen that channels are correlated (the coefficients are almost the same).

BER for BPSK modulation with 2×2 MIMO and ZF equalizer (Rayleigh channel).

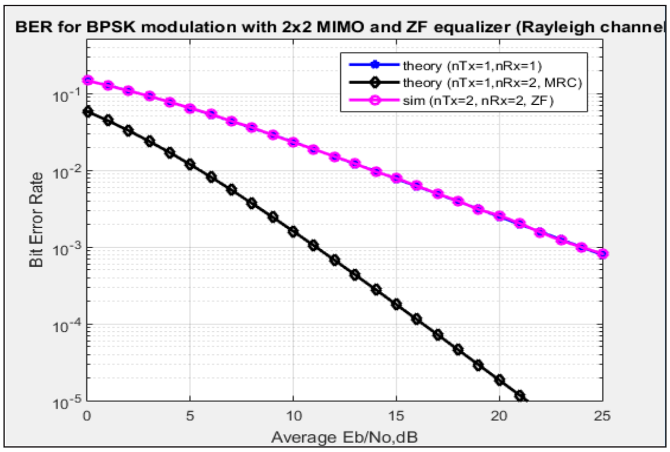

Fig. 3: BER Plot for 2×2 MIMO Channel with ZF Equalizer (BPSK Modulation in Rayleigh Channel)

BER for BPSK modulation with 4×4 MIMO and ZF equalizer (Rayleigh channel).

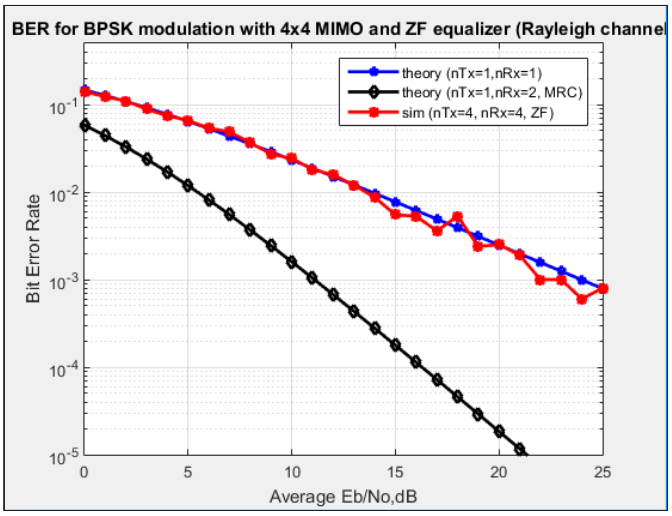

Fig. 4: BER Plot for 4×4 MIMO Channel with ZF Equalizer (BPSK Modulation in Rayleigh Channel)

Fig. 4 shows that as a result of increasing SNR, BER decreases and the number of receiving antennas is improved. In the case of 4×4 MIMO shown in Fig. 4 has some discontinuity due to interference effects.

The following observations are made. The Zero Forcing Equalizer dispels all ISI and it remains ideal only when the channel is noiseless. When the channel is noisy, the Zero Forcing Equalizer will not perform well and enhances the noise comprehensively and has a small magnitude (i.e. near to zero). ZF Equalizer completely ignores the noise effect and is not enough for wireless communication links. However, it performs well for static channels with high SNR.

B. Simulation Analysis for MMSE

BER for BPSK modulation with 2×2 MIMO and MMSE equalizer (Rayleigh channel).

Fig. 5 shows that for MMSE equalizer the number of receiver and transmitter is 2×2.

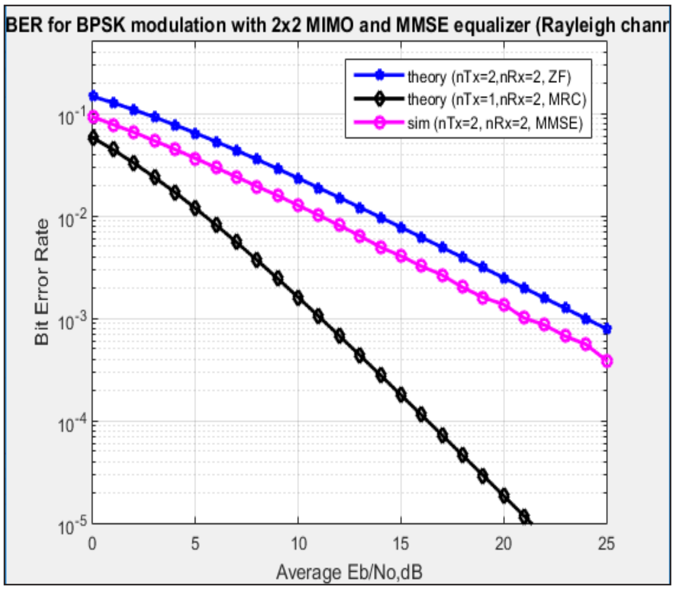

Fig. 5: BER Plot for 2×2 MIMO Channel with MMSE Equalizer (BPSK Modulation in Rayleigh Channel)

From the above Fig. 5 shows that two equalizers are performed namely ZF and MMSE. It is observed that Bit Error Rate (BER) for MMSE decreases than ZF with the increase of SNR and MMSE achieves better performances than the ZF equalizer. Moreover, MMSE is a better performance than ZF.

BER for BPSK modulation with 4×4 MIMO and MMSE equalizer (Rayleigh channel).

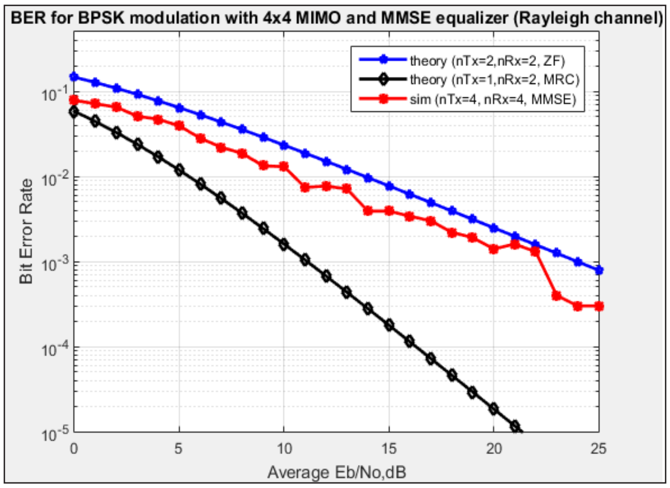

Fig. 6: BER Plot for 4×4 MIMO Channel with MMSE Equalizer (BPSK Modulation in Rayleigh Channel)

Fig. 6 shows that it has some discontinuity due to interference-effect. From the above graphs, it is summarized that if the number of receiving antenna increases as well as transmitting antenna in MMSE equalizer then BER will decrease.

In the following Table I shows BER values comparison between the ZF and MMSE equalizer in (2×2) and (4×4) MIMO system. From the Table it is seen that in both cases when the $\frac{E_b}{N_0}$ values are serially increased then the BER values are gradually decreased. In addition, this table analyses that simulated bit error rate (simBer) of MMSE is much smaller than ZF in both (2×2) and (4×4) MIMO system.

Table I: BER Values Comparison between the ZF and MMSE Equalizer in (2×2) and (4×4) MIMO System

$\frac{E_b}{N_0}$	BER Values for ZF and MMSE Equalizer in (2×2) and (4×4) MIMO System			
	simBer ZF 2×2	simBer MMSE 2×2	simBer ZF 4×4	simBer MMSE 4×4
0	0.1450	0.0945	0.1363	0.0884
1	0.1307	0.0804	0.1313	0.0681
2	0.1057	0.0673	0.1054	0.0596
3	0.0935	0.0531	0.0834	0.0495
4	0.0740	0.0441	0.0772	0.0477
5	0.0603	0.0352	0.0679	0.0386
6	0.0537	0.0285	0.0493	0.0279
7	0.0437	0.0243	0.0407	0.0268
8	0.0340	0.0182	0.0380	0.0197
9	0.0329	0.0152	0.0311	0.0170
10	0.0222	0.0123	0.0234	0.0133
11	0.0171	0.0099	0.0196	0.0089
12	0.0162	0.0080	0.0168	0.0086
13	0.0138	0.0057	0.0123	0.0058
14	0.0107	0.0065	0.0115	0.0053
15	0.0074	0.0047	0.0077	0.0030
16	0.0059	0.0031	0.0064	0.0040
17	0.0063	0.0026	0.0035	0.0025
18	0.0043	0.0027	0.0032	0.0018
19	0.0031	0.0018	0.0034	0.0018
20	0.0020	0.0013	0.0018	0.0017
21	0.0019	0.0012	0.0019	0.0009
22	0.0011	0.0007	0.0016	0.0005
23	0.0009	0.0004	0.0014	0.0003
24	0.0014	0.0003	0.0007	0.0010
25	0.0005	0.0003	0.0007	0.0002

Based on the simulation results analyzed so far, it is concluded that MMSE is more accurate and suits a wide range of channel state conditions expressed in SNR ratio. The zero forcing method is an approximate method more suitable for high signal to noise ratio.

The MMSE is working well for all signal to noise ratios but it needs much more computational effort.

VII. Conclusion

This paper has tried to display the particular information about the Zero Forcing (ZF) and Minimum Mean Square Error (MMS) Equalizer as well as show the comparison of performance between them based on the MIMO receiver. All the simulation results will be shown about the Bit Error Rate (BER) features for both types of equalizers. This paper uses the RF signal processing lab framework for the analysis of simulation.

By analyzing all the simulation results it will be concluded that the Zero forcing equalization does not satisfy some condition. Firstly, with the increasing the value of the signal to noise ratio it will not work well i.e. it is considered to be a good receiver under noise-free conditions. Secondly, the channel may consist of zeros in its frequency response but that cannot be reversed. And thirdly, the channel impulse response has finite length but due to finite-length, it does not fulfil all conditions. For these limitations, ZF is not better performed than MMSE.

Based on the simulation results for MMSE we can summarize that MMSE equalizer based receiver is more accurate and suits a wide range of channel state conditions expressed in SNR ratio. ZF equalizer enhances the noise in the channel while the MMSE equalizer provides better noise immunity and removes a marginal noise. Furthermore, Zero Forcing and MMSE equalizers were simulated and the results compared. The results show that MMSE equalizer performs better than ZF equalizer.

References

[1] D. Gesbert, M. Shafi, D. Shiv, and P. J. Smith, “From theory to practice: An overview of MIMO space time coded wireless system,” *IEEE Journal on Selected Areas in Communication*, vol. 21, no. 3, pp. 281-301, 2003.

[2] X. Zhang, and S. Kung, “Capacity analysis for parallel and sequential MIMO equalizers,” *IEEE Transactions on Signal Processing*, vol. 51, pp. 2989-3002, 2003.

[3] I. E. Telatar, “Capacity of multi-antenna Gaussian channels,” *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585-595, November-December 1999.

[4] V. Tarokh, A. Naguib, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communication: Performance criteria in the presence of channel

estimation errors, mobility, and multiple paths," *IEEE Transactions on Communications*, vol. 47, no. 2, pp. 199-207, 1999.

[5] J. Meiyan, J. Qian, Y. Li, G. Tan, and X. Li, "Comparison of multiuser MIMO systems with MF, ZF and MMSE receivers," *2013 IEEE Third International Conference on Information Science and Technology (ICIST)*, 2013.

[6] T. Abdessalem, et al., "Performance analysis of ZF and MMSE equalizers for MIMO systems," *7th International Conference on Design & Technology of Integrated Systems in the Nanoscale Era*, IEEE, 2012.

[7] B. M. Hochwald, and T. L. Marzetta, "Unitary space-time modulation for multiple-antenna communication in Rayleigh flat fading," *IEEE Transactions on Information Theory*, vol. 46, pp 543-564, March 2000.

[8] D. Malik, and D. Batra, "Comparison of various detection algorithms in a MIMO wireless communication receiver," *International Journal of Electronics and Computer Science Engineering*, vol. 1, no. 3 pp. 1678-1685, 2012.

[9] A. J. Paulraj, D. Gore, R. Nabar, and H. Bolcskei, "An overview of MIMO communications – A key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, pp. 198-218, February 2004.

[10] J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, "Channel measurements for large antenna arrays," *Proceedings of International Symposium on Wireless Communication Systems (ISWCS),* pp. 811-815, August 2012.

[11] G. J. Foschini, D. Chizhik, M. Gans, C. Papadias, and R. A. Valenzuela, "Analysis and performance of some basic space-time architectures," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 303-320, April 2003.

[12] Y. Jiang, M. K. Varanasi, and J. Li, "Performance analysis of ZF and MMSE for MIMO systems: An in-depth of the high SNR regime," *IEEE Transactions on Information Theory*, vol. 57, no. 4, April 2011.

[13] A. Kumar, and P. Vardhan, "Design, simulation & concept verification of 4×4, 8×8 MIMO with ZF, MMSE and BF detection schemes," *Electrical, Control and Communication Engineering*, vol. 13, no. 1, pp. 69-74, 2017.

[14] N. Prasad, and M. K. Varanasi, "Analysis of decision feedback detection for MIMO Rayleigh fading channels and the optimization of rate and power allocations," *IEEE Transactions on Information Theory*, vol. 50, pp. 1009-1025, June 2004.