Hybridization of zero forcing-minimum mean square error equalizer in multiple-input multiple-output system

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ABSTRACT

Transmission of high data rate over multipath environment is associated with many wireless applications. However, this transmission results in high delay which leads to inter-symbol interference (ISI) distortion and causes high error. The existing linear equalizer (LE) in multiple-input multiple-output (MIMO) systems such as zero forcing (ZF) equalizer used in addressing this problem reduces the ISI distortion completely but results in noise amplification. Likewise, minimum mean square error (MMSE) equalizer only reduces the noise but cannot eliminate ISI. Therefore, this paper proposed a hybrid LE for wireless fidelity (Wi-Fi) over Weibull fading channel. The hybridized ZF-MMSE equalizer was developed using conventional ZF and MMSE equalizers. Digital transmitted signal propagated over Weibull fading channel is received at the receiver through multiple antennas and then combined using maximal-ratio combining (MRC). The combined signal is then equalized using hybrid ZF-MMSE to eliminate both the ISI and the amplified noise. The developed model was simulated in MATLAB software environment and evaluation was performed using bit error rate (BER) and pout. The results obtained revealed that the hybrid ZF-MMSE equalizer gave better performance over existing equalizers in a MIMO system. Therefore, the proposed equalizer will help improve the performance of the Wi-Fi technology.

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1. INTRODUCTION

Nowadays, wireless communication is undergoing a strong expansion due to its applications in various facet of human endeavor. The remarkable growth of wireless services over the last decade demonstrates the massive and increasing demand for wireless networks. Wireless fidelity (Wi-Fi) is one major backbone of internet access and a branch of the third generation (3G) and beyond technologies which support multimedia services [1]. This technology is saddled with the interconnectivity of hundreds of millions of network subscribers for seamless and reliable data transmission. To ensure improvement in data transmission rate, network capacity, communication link reliability and good quality-of-service (QoS), multiple-input multiple-output (MIMO) systems were deployed. This helps to combat the effect of multipath propagation which degrades the quality of the transmitted signal in wireless communication environment [2]–[4].

Multipath propagation is a phenomenon that occurs at the channel of the wireless communication system with the transmitted signals exhibiting different impairment effects. These effects result in fading of the propagated signals due to delay spread and subsequently leads to inter-symbol interference (ISI) and noise enhancement. In order to address this problem, there have been many methods reported in the literature. Rake receivers is a traditional technique used in adjusting the effect of channel on transmitted signal by means of time-shift spreading sequence [5]. Another technique is the orthogonal frequency division multiplexing (OFDM) with the ability to mitigate adverse channel effect such as ISI without employing complex equalizer, however, this technique exhibits noise amplification [6].

In addition, MIMO system is a configuration of multiple antenna deployment at both the transmitter and receiver. This technique reduces the multipath effects experienced by the transmitted signal [7] which results in some unacceptable errors and deteriorates the system performance. In view of these, equalization becomes important. Equalization technique is another method used at the receiver to eliminate ISI as a result of channel distortion in order to improve the reliability and quality of the received signal. Equalizers can be classified as non-linear and linear equalizers [8], [9].

The non-linear counterpart is a feedback equalizer which changes the successive output of the equalizer without consideration for the noise effect [10]. The equalizers that fall into this category includes: maximum likelihood (ML), decision feedback equalizer (DFE), and maximum likelihood sequence estimation (MLSE) [10], [11]. On the other hand, linear equalizer refers to as feed-forward filter such as zero forcing (ZF) and minimum mean square error (MMSE) equalizers. However, these techniques reduced the ISI but suffers from noise amplification [12]. Research interest in ZF equalizer revealed that the equalizer possesses the ability to eliminate ISI with the aid of perfect channel state information (CSI) but degrades due to noise enhancement factor [13].

On the other hand, MMSE equalizer is used to minimize the mean square error and has been revealed to possesses similar behaviour as ZF equalizer at high signal-to-noise ratio (SNR) while exhibiting matched filter characteristics at low SNR [12], [14]. However, it does not completely eliminate ISI and this limits the performance of wireless system applications [15]. There have been various existing works on equalizers which focused on reduction of ISI in wireless communication systems. Kumar *et al*. [9] performed a comparative analysis of M-ary phase shift keying (M-PSK) and M-ary quadrature amplitude modulation (M-QAM) schemes on least mean square (LMS) and recursive least square (RLS) equalizers over Rayleigh fading channel. The channel impulse response was normalized by using a maximum response value in order to reduce the channel distortion in wireless communication system. The result obtained showed that the effect of ISI was minimized while the noise amplification effect was not taken into consideration.

Gupta and Grover [16], the performance analysis of MIMO systems under multipath fading channels using different equalization techniques were presented. The authors investigated different equalizers such and ZF, MMSE, zero forcing-successive interference cancellation (ZF-SIC), minimum mean square error-successive interference cancellation (MMSE-SIC), ML, and sphere decoder to mitigate the effect of ISI and noise amplification. The results obtained showed that there was a better performance in bit error rate (BER) with reduced ISI and noise amplification for the equalizers with SIC under studied. However, the equalizers are hindered by implementation complexities. In the work of [12], the combination of ZF, MMSE, and SIC linear equalizer over Rayliegh fading channel for MIMO systems was proposed to eliminate ISI, noise enhancement and other interference. The result obtained showed that better ISI reduction performance was archieved as compared to individual conventional equalizers in terms of BER at high SNR regime.

Waliullah *et al.* [15], the study of ZF and MMSE equalizers using binary phase shift keying (BPSK) modulation in MIMO systems was evaluated. The problem of ISI on received signal was investigated in multipath fading environment. The result shows that MMSE outperforms ZF in additive white Gaussian noise (AWGN) channel. This is because MMSE equalizer provides a better noise immunity with marginal interference mitigation while ZF enhances noise in the channel. AL-Qaysi *et al*. [17] worked on the BER performance of different quantization resolution levels on massive MIMO systems under different operating scenarios. In the work, MMSE was employed to mitigate the effect of inter user interference of the vector of the transmitted signal symbols from the vector of the received signal symbols. The adoption of the MMSE was due to its low computational complexity, good noise improvement and superiority over ZF detector. Mishra and Roy [18] used an adaptive signal processing algorithm as an equalization technique to address the problem of ISI in a MIMO system. The technique improved the performance of MIMO system whenever the tap coefficient is increased and the signal's output converges. However, noise amplification increases linearly whenever the tap weight coefficients increase.

Based on the reviewed literature, it is very evidence that existing works on the simultaneous mitigation of ISI and noise amplification which reduces the quality of the received signal in wireless communication systems has received little attention. Also, the review of literature shows that most works focused on AWGN and Rayleigh fading channels. Therefore, the contribution of this paper is to mitigate the effect of ISI and amplified noise in MIMO systems using hybridized ZF-MMSE equalizer over Weibull fading channel which is a composite channel that combines both aquatic and terrestrial environment. This will help in improving the system performance and provide a better QoS to the network users. The paper is organized as: i) section 2 represents the proposed model; ii) section 3 shows the simulation result; and iii) section 4 conclude our work.

2. METHOD
2.1. Hybrid zero forcing-minimum mean square error equalizer

The hybrid ZF-MMSE equalizer is achieved by cascading the ZF and MMSE equalizers at the output side of the MIMO channel as depicted in Figure 1. This is to improve the performance of the system by ensuring that the ISI and noise amplification inherent in the conventional ZF and MMSE are mitigated. In this section, a closed form expression for the hybrid model for BER and outage probability are derived using the SNR and probability density function (PDF) of the received signal.

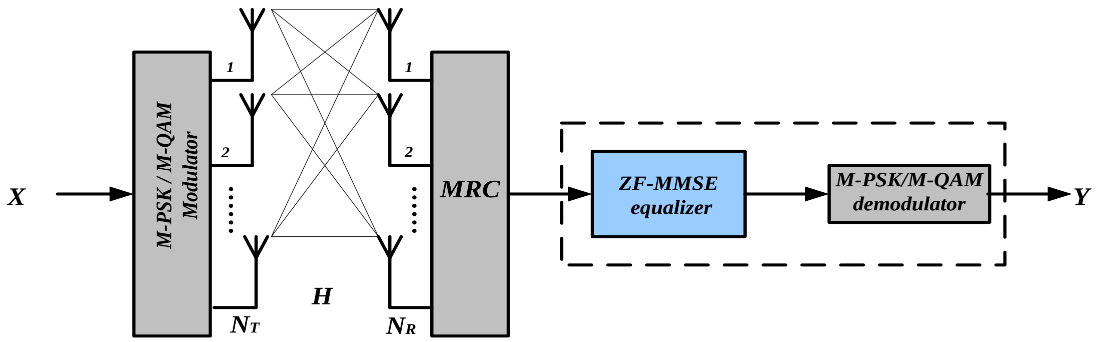

Figure 1. MIMO system with hybrid ZF-MMSE equalizer

2.2. SNR analysis of the hybrid ZF-MMSE equalizer with MRC

The received signals of the hybrid ZF-MMSE equalizer for MIMO system is given in [19] expressed as (1):

$$y = Hx + n \tag{1}$$

where, y is the received signal and has a dimension of $[N_R \times 1]$, x is the transmitted signal and has a dimension of $[1 \times N_R]$, n is the noise with dimension $[N_T \times 1]$ and H is the time-varying Weibull MIMO channel with dimension $[N_R \times N_T]$ and is given as (2).

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1} & h_{N_R,2} & \cdots & h_{N_R,N_T} \end{bmatrix} \tag{2}$$

The received signal experiences channel distortion due to the fading characteristics of Weibull distribution, which severely affects the quality of the transmitted signal. In order to mitigate this channel effect, the received signal after combining with MRC combiner is passed through a hybrid ZF-MMSE equalizer. This is achieved by multiplying the weight coefficient of the equalizer with the received signal in (1) which is obtained as (3):

$$W_{ZF-MMSE}\,y = W_{ZF-MMSE}[Hx + n] \tag{3}$$

where, $W_{ZF-MMSE}$ is the weight coefficient of the hybrid equalizer. The hybrid equalizer in (3) used in the model is obtained by cascading both ZF and MMSE equalizers and is expressed as (4).

$$W_{ZF-MMSE} = W_{ZF} \times W_{MMSE} \tag{4}$$

The weight coefficient of ZF equalizer is given by [20] as (5):

$$W_{ZF} = [H^H H]^{-1} H \tag{5}$$

where, H^H is the Hermitian transpose of the MIMO system channel H. Similarly, the weight coefficient of MMSE equalizer is given by [21] as (6):

$$W_{MMSE} = \left[H^H H + \frac{1}{snr} I\right]^{-1} H^H \tag{6}$$

where, $snr = \frac{\sigma_x^2}{\sigma_N^2}$ is the ratio between variance of transmitted signal and noise variance and I is an identity matrix. The expression in (4) is simplified by substituting (5) and (6) to yield, expressed as (7).

$$W_{ZF-MMSE} = \left[H^H H + \frac{1}{snr} I\right]^{-1} \tag{7}$$

The output SNR of the received signal after passing through MRC in (1) is expressed by [22] as (8):

$$\gamma_s = \frac{1}{K} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \frac{E_s}{N_o} \left|h_{i,j}\right|^2 \tag{8}$$

where, γ_s is the output SNR after MRC combiner, $h_{i,j}$ is the instantaneous Weibull fading channel for an independent and identically distribution (i.i.d) circular complex Gaussian random variables, E_s is the average energy per symbol of the transmit antenna and N_o is the noise power spectral density of the AWGN. Therefore, the output SNR of the received signal after passing through the hybrid ZF-MMSE equalizer $\gamma_{ZF-MMSE}$ is obtained as (9).

$$\gamma_{ZF-MMSE} = \gamma_s \left[H^H H + \frac{1}{snr} I\right] \tag{9}$$

2.3. Probability density function of the equalized signal

The PDF of the equalized received signal $f_{\gamma_k}(\gamma_{ZF-MMSE})$ is obtained by substituting (9) into the PDF of Weibull fading channel according to [22], [23] which yields as (10):

$$f_{\gamma_{ZF-MMSE}}(\gamma_{ZF-MMSE}) = \frac{\beta \gamma_{ZF-MMSE}^{\frac{\beta}{2}-1}}{2\alpha_{i,j}^{\beta/2}} exp\left[-\left(\frac{\gamma_{ZF-MMSE}}{\alpha_{i,j}}\right)^{\frac{\beta}{2}}\right] \tag{10}$$

where, β is the shaping parameter, $\alpha_{i,j} = \boldsymbol{\lambda}_{i,j}/\Gamma(1+\frac{2}{\beta})$ is the scale parameters and $\Gamma(\cdot)$ is a Gamma function. According to [22], by applying the Jacobian transformation to (10) yields as (11).

$$f_{\gamma_{ZF-MMSE}}(\gamma_{ZF-MMSE}) \approx \frac{\beta}{\gamma_{ZF-MMSE}} exp\left(-\left(\frac{\sigma}{\alpha}\gamma_{ZF-MMSE}\right)^{\frac{\beta}{2}}\right)\left(\sum_{i=0}^{N_T N_R-1} \frac{\left(\frac{\sigma}{\alpha}\gamma_{ZF-MMSE}\right)^{\frac{\beta}{2}(i+1)}}{i!} - \sum_{i=1}^{N_T N_R-1} \frac{\left(\frac{\sigma}{\alpha}\gamma_{ZF-MMSE}\right)^{\frac{\beta}{2}i}}{(i-1)!}\right) \tag{11}$$

Performing mathematical operation, the $f_{\gamma_{ZF-MMSE}}(\gamma_{ZF-MMSE})$ obtained in (11) can be approximated as (12):

$$f_{\gamma_{ZF-MMSE}}(\gamma_{ZF-MMSE}) \approx \frac{N_T N_R \beta\theta}{2(N_T N_R-1)!} (\theta N_T N_R \gamma_{ZF-MMSE})^{\frac{\beta N_T N_R}{2}-1} exp\left(-(\theta N_T N_R \gamma_{ZF-MMSE})^{\frac{\beta}{2}}\right) \tag{12}$$

which represents the PDF of generalized gamma random variables with parameters $(\frac{1}{\theta}, \frac{\beta N_T N_R}{2}, \frac{\beta}{2})$ and $\theta = \frac{\sigma}{\alpha} = \frac{\Gamma\left(N_T N_R + \frac{2}{\beta}\right)}{N_T N_R!ג}$.

2.4. BER analysis of the hybrid equalizer

In this section, the BER analysis of the hybrid ZF-MMSE equalizer using M-PSK and the M-QAM are presented**.** In this paper, the BER expression of MMSE over Weibull fading channel at $\beta = 2$ is employed for the modulation schemes of the Wi-Fi technology which are the BPSK, quadrature phase shift keying (QPSK), 4-quadrature amplitude modulation (4QAM) and 16-quadrature amplitude modulation (16QAM). The reason for the choice is because the output of the ZF equalizer is used as the input to the MMSE equalizer and that Weibull fading reduces to Rayleigh.

2.4.1. BER analysis using M-PSK modulation scheme

Utilizing the BER of MMSE for BPSK modulation scheme presented in the work of Jiang *et al.* [11] the BER of hybrid ZF-MMSE for BPSK is obtained by substituting the received SNR in (9) which yields; expressed as (13):

$$P_{b_{BPSK}}^{ZF-MMSE} = E\left[Q(\sqrt{2(\gamma_{ZF-MMSE}})\right] \tag{13}$$

where, $E\,[\cdot]$ is the expectation function and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}dt$ is the standard Gaussian Q function. Similarly, the BER analysis of the hybrid ZF-MMSE equalizer for QPSK scheme using the expression given by [24] and substituting the received SNR obtained in (9) yields; expressed as (14).

$$P_{b_{QPSK}}^{ZF-MMSE} = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_{ZF-MMSE}}{1+\gamma_{ZF-MMSE}}}\right) \tag{14}$$

2.4.2. BER analysis using M-QAM modulation scheme

The hybrid ZF-MMSE equalizer at the receiver of the MIMO system for 4QAM modulation scheme is obtained using [25] and then putting the received SNR is expressed as (15).

$$P_{b_{4QAM}}^{ZF-MMSE} = \left[Q\left(\sqrt{\gamma_{ZF-MMSE} - 3.9dB}\ \right)\right] \tag{15}$$

Similarly, using the BER for 16QAM modulation scheme expressed according to [26] and substituting the received SNR yields; expressed as (16).

$$P_{b_{16QAM}}^{ZF-MMSE} = \frac{3}{4}\ Q\left(\sqrt{\frac{4}{5}\gamma_{ZF-MMSE}}\right) - \frac{9}{16}\ Q^2\left(\sqrt{\frac{2}{7}\gamma_{ZF-MMSE}}\right) \tag{16}$$

2.5. Outage probability analysis of the hybrid equalizer

The outage probability P_{out} of the equalized received signal can be expressed according to [27] as (17).

$$P_{out} = \int_0^{\gamma_{th}} f_{\gamma_{th}}(\gamma)d\gamma = \Pr(\gamma_{ZF-MMSE} \leq \ \gamma_{th}) = F_{\gamma_{i,j}} \tag{17}$$

Where, $F_{\gamma_{i,j}}$ is the cumulative density function (CDF) and γ_{th} is the threshold SNR. According to [22] by taking the CDF of (11), the outage probability of the MIMO system with ZF-MMSE equalizer is obtained as (18).

$$F_{\gamma_{th}}(\gamma_{ZF-MMSE}) = 1 - exp\left(-\left(\frac{\sigma\,\gamma_{ZF-MMSE}}{\alpha}\right)^{\frac{\beta}{2}}\right)\sum_{i=0}^{N_T N_R-1}\frac{\left(\frac{\sigma\,\gamma_{ZF-MMSE}}{\alpha}\right)^{\frac{\beta}{2}i}}{i!} \tag{18}$$

Where, $\sigma = \frac{\Gamma\left(N_T N_R + \frac{2}{\beta}\right)}{(N_T N_R)!\Gamma\left(1+\frac{2}{\beta}\right)}$ is chosen as an approximation distribution equivalent to the convolution distributions. The outage probability obtained in (18) can be further simplified to yield, expressed as (19).

$$F_{\gamma_{th}}(\gamma_{ZF-MMSE}) \approx 1 - exp\left(-(\theta N_T N_R \gamma_{th})^{\frac{\beta}{2}}\right)\sum_{i=0}^{N_T N_R-1}\frac{(\theta N_T N_R \gamma_{th})^{\frac{\beta}{2}i}}{i!} \tag{19}$$

3. SIMULATION RESULT

In this section, the simulation of the MIMO system with hybrid ZF-MMSE equalizer for Wi-Fi technology over Weibull fading channel is presented. The simulation was carried out using MATLAB R2018a software. The simulation parameters used are as presented in Table 1.

Table 1. Simulation parameters

Parameter	Specification
Data length	10000
Number of antennas	2×2, 4×4
Carrier frequency	5 GHz
Channel	Weibull fading channel
Noise	AWGN
Transmit and recieve filter	Square root raised cosine
SNR	0:2:20
SNR threshold	3 dB
Roll off factor	0.25
Filter gain	5 dB

3.1. BER performance

Figures 2 and 3 present the BER against SNR for different equalizers using BPSK modulation scheme for different antenna configurations and a 4×4 MIMO systems with different modulation schemes over Weibull fading channel. The results show that as the antenna configuration increases, the BER values decreases. This implies that by transmitting at high data rate over the Weibull fading channel, lesser bits are received in error.

For instance, in Figure 2, a 2×2 MIMO system, at SNR of 8 dB, the BER values obtained were 1.34×10^{-2}, 1.07×10^{-2} , and 3.5×10^{-3} for ZF, MMSE, and the hybrid ZF-MMSE equalizers for BPSK modulation scheme, respectively. On the other hand, at SNR of 16 dB, the BER obtained were 1.7×10^{-3}, 8.0×10^{-4}, and 3.0×10^{-4} for ZF, MMSE, and the hybrid ZF-MMSE equalizers, respectively. In the case of the 4×4 antenna configuration of the MIMO system, the BER values of 2.1×10^{-3}, 1.7×10^{-3}, and 6.0×10^{-4}, were recorded for ZF, MMSE and ZF-MMSE equalizers, respectively at SNR of 10 dB, while at 16 dB, BER of 1.0×10^{-3}, 8.86×10^{-5}, and 4.35×10^{-5}, respectively. Similarly, as the SNR increases, the BER values for both the 2×2 and 4×4 for all the equalizers reduces. The hybrid ZF-MMSE equalizer shows a superiority over the ZF and MMSE equalizer by reducing the ISI and noise enhancement that deteriorates the performance of the system.

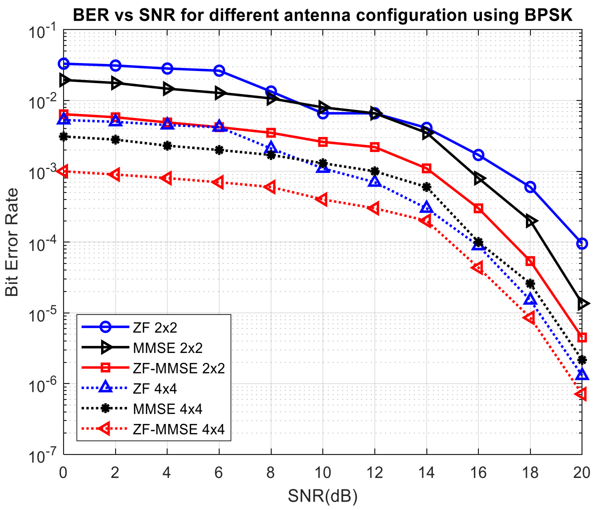

Figure 2. BER vs SNR for different equalizers using BPSK modulation scheme for different antenna configurations

In Figure 3, with increasing number of transmitting and receiving antennas with different modulations, the result obtained depict that the higher the modulation order, the higher the BER value obtained. However, the BER decreases as the SNR values increases. This illustrates that by increasing the constellation sizes of both M-PSK and M-QAM of the transmitted signal under an unfavourable channel condition, the BER performance of the system degrades at the expense of increased data rate.

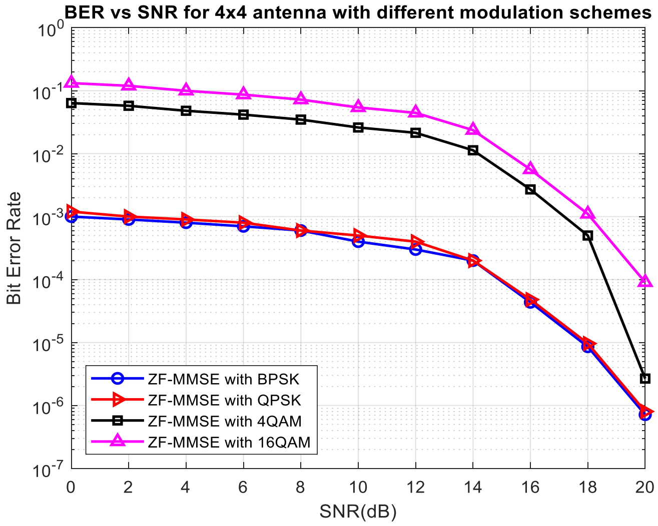

Figure 3. BER vs SNR for a 4 × 4 MIMO systems with different modulation schemes

3.2. Outage performance

The performance of the hybrid ZF-MMSE in terms of outage probability with different antenna and modulation schemes were presented in Figures 4 and 5. The result obtained in Figure 4 illustrates that the outage probability of 4×4 MIMO system outperforms that of the 2×2 MIMO system using BPSK modulation scheme. At SNR of 10 dB, the outage probability obtained were 4.87×10^{-2}, 4.38×10^{-2}, and 2.83×10^{-2}, for ZF, MMSE, and ZF-MMSE, respectively for the 4×4 MIMO system, while 7.7×10^{-3}, 1.12×10^{-2}, and 1.1×10^{-2} were obtained for the 2×2 MIMO system.

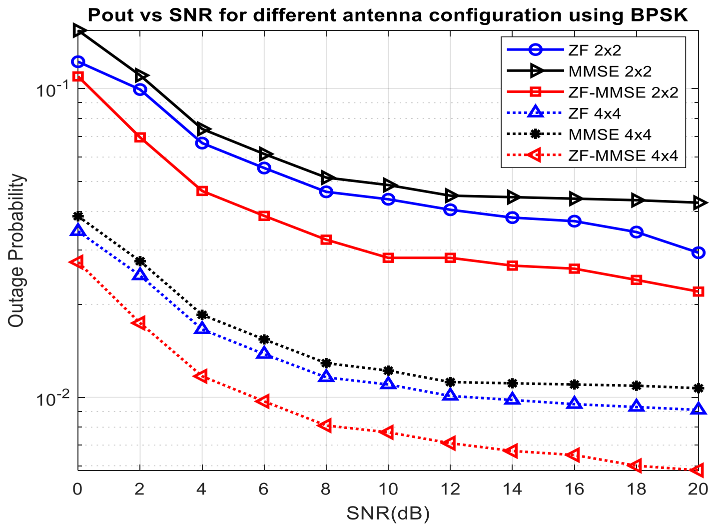

Figure 4. Outage probability vs SNR for different antenna configurations with BPSK modulation scheme

In Figure 5, different modulation schemes were used to test the performance of the hybrid ZF-MMSE equalizer. The result obtained shows that the outage probability decreases with increase in SNR. In addition, as the constellation sizes of each modulation schemes increase, more outages were observed but decreases with increase in the antenna configuration.

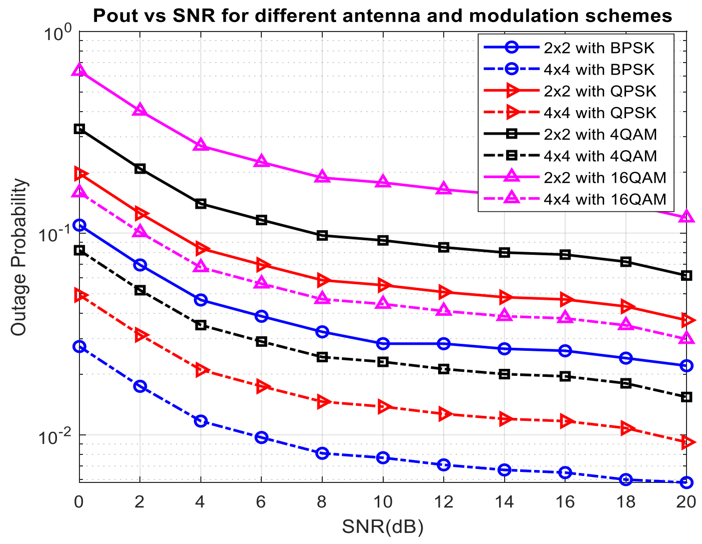

Figure 5. Outage probability vs SNR for ZF-MMSE using different antenna configurations and modulation scheme

4. CONCLUSION

In this paper, a hybrid ZF-MMSE equalizer for MIMO system over Weibull fading channel has been proposed. The existing ZF and MMSE equalizers used suffer from ISI and noise amplification which impact the performance of the Wi-Fi technology with multiple antenna deployment. To address these problems, ZF and MMSE equalizers have been designed in such a way that the received signal after passing through the MRC combiner is first equalized using ZF section and the output is feed as input to the MMSE section. The PDF of the received SNR analyzed over Weibull fading channel was then obtained by applying the Jacobian transform. In addition, the closed form expression of the BER and the outage probability were derived using the SNR and PDF analyzed, respectively. Simulation of the proposed model was then carried out in MATLAB R2018a software. The evaluation was then performed using BER and outage probability with M-PSK and M-QAM modulation schemes according to the Wi-Fi technology standard. The results obtained revealed that the hybrid ZF-MMSE outperformed the conventional ZF and MMSE equalizers, respectively in terms of BER and outage probability at different antenna configurations. Hence, this implies that the proposed ZF-MMSE equalizer shows reduction in both ISI and noise amplification which is more efficient in M-PSK modulation scheme at the expense of M-QAM modulation scheme in high data transmission.

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