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Error Rate Performance Investigations of MIMO Transmission Modes through Nakagami-m Fading Channels

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Abstract

In the field of wireless communication systems, the use of multiple antennas at the transmitter and receiver side has gained a huge popularity over the past few decades, due to its tremendous performance enhancing capabilities. Such systems are known as MIMO (Multiple-Input Multiple-Output) systems and can be classified into three main categories; Spatial Multiplexing, Spatial Diversity and Beam forming techniques. The objective of this paper is to evaluate the error rate performance of MIMO transmission modes through Nakagami-m fading channels. The ZF (Zero Forcing), MMSE (Minimum Mean-Square-Error) channel equalization algorithm; STTC (Space Time Trellis Codes), OSTBC (Orthogonal Space Time Block Codes), MRC (Maximal Ratio Combining) and Beamforming methods are analyzed. The QPSK modulation technique is used to evaluate the bit error rate (BER) performances under different SNR scenarios. The results described in this paper suggest considerable improvement in the system performance by incorporating different MIMO techniques in order to improve the wireless transmission link quality.

Keywords: *Spatial Multiplexing, Spatial Diversity, Beamforming, BER, Error probability*

1. Introduction

In the never-ending research for increased capacity in wireless communication channels, it has been revealed that by using multi-antenna systems it is possible to increase that capacity significantly. Such multi-antenna systems are known as Multiple Input Multiple Output (MIMO) systems that fulfills the promise of high data rates with increased spectral efficiency [1]. MIMO systems can be implemented in different ways to either obtain a diversity gain to combat the fading or to obtain a capacity gain [2]. In general, there are three categories of MIMO techniques; the first technique aims to improve the power efficiency by maximizing diversity gain and is known as Spatial Diversity. Such techniques include STBC and STTC [3]. The second class intended to increase the channel capacity, are known as Spatial multiplexing (SM). In SM, a high rate data signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel so that the receiving antenna array receives a superposition of all the transmitted signals [4]. Thus MIMO capacity raises linearly with min (N_T,N_R) as compared to the single input single output (SISO) systems, where N_T and N_R is number of transmitter and receiver antenna respectively [5]. The third type is referred as Beamforming technique that exploits the channel knowledge at the transmitter [6]. Beamforming techniques are used to generate the radiation pattern of antenna array. Precoding is a generalization of beamforming to support multi-layer transmission in multi-antenna wireless communications. The MIMO channels offer several advantages over conventional single antenna channels, as follows:

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MIMO systems offer a linear increase in data rate through spatial multiplexing technique. With N_T transmit and N_R receive antennas, the min (N_T, N_R) number of data streams can be reliably supported by a MIMO channel [6]. The gain achieved in terms of bit rate (with respect to a single-antenna system) is called Multiplexing gain [1]. Spatial Diversity gain is the improvement in communication link reliability obtained by receiving replicas of the information signal through fading channels [6]. By means of two-dimensional coding in time and space, known as space-time coding (STC), the information sequence is transmitted over multiple transmit antennas. Well-known spatial diversity techniques for systems with multiple transmit antennas are, Alamouti's transmit diversity [2], orthogonal space time block codes (OSTBC) as well as space-time trellis codes (STTC) [7-8]. Multiple-antenna techniques can also be utilized to improve the signal-to-noise ratio (SNR) at the receiver and to suppress co-channel interference in a multiuser (MU) systems by means of adaptive antenna arrays, also called smart antennas or Beamforming [2]. The improvement in received SNR resulting from a coherent combining effect of the information signals is represented by Array gain [6]. On the whole, multi-antenna techniques constitute a key technology for modern wireless communications.

In digital transmission, the number of receiving bits of a signal data over a communication channel is changed because of the noise, distortion, interference or bit synchronization redundancy. Hence, it is important for the system designers and engineers to evaluate and analyse the BER of MIMO systems under different fading channels. The bit error rate/bit error ratio (BER) is the rate, at which the bit errors occur in a transmission system during a premeditated time interval [9]. In this paper error rate analysis under Nakagami-*m* fading channel is presented using different equalizers such as ZF, MMSE; different diversity techniques as receive and transmit diversity (space time codes); and beam forming techniques. The different transmission modes of multi-antenna systems based on their functions are briefly described in Section 2. The channel model used is exemplified in Section 3. The simulation environment and methodology used is illustrated in Section 4. And the results obtained from simulations are discussed and compared in Section 5.

2. Function of MIMO Systems

Given the advantages that can be drawn by diversity and spatial multiplexing gains, MIMO can be sub-divided into three main categories, as described in this section:

2.1. Spatial Multiplexing

Spatial multiplexing (SM) is a transmission technique in MIMO wireless communications to transmit independent and separately encoded data signals from each of the multiple transmits antennas [1]. The capacity of a MIMO systems with N_T transmit and N_R receive antennas grows linearly with the min (N_T, N_R) [10] without requiring extra bandwidth or extra transmission power [2]. The spatial channels are de-multiplexed at the receiver in order to detect the transmitted symbols. For lower complexity, a linear receivers are used, e.g., based on the zero-forcing (ZF) or the minimum-mean-squared-error (MMSE) algorithm. However, the error performance is typically poor, especially when the ZF technique is used [2]. The generalized block diagram of MIMO detection technique is shown in Figure 1.

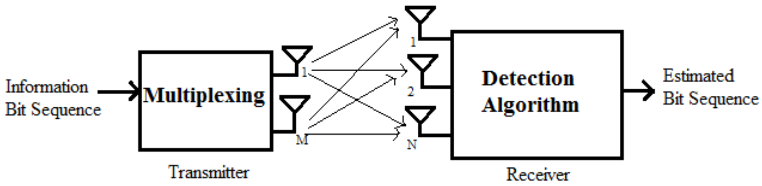

Figure 1. Basic Principle of Spatial Multiplexing [2]

The ZF is a linear estimation technique used in communication systems, which inverse the frequency response of received signal and the inverse is taken to restore the signal after channel. The estimation of the strongest transmitted signal can be obtained by nulling out the weaker transmit signal [6]. Thus the name ZF corresponds to bringing down the Inter symbol Interference (ISI) to zero in noise free scenarios [4]. MMSE equalizer minimizes the mean–square error between the equalizer output and the transmitted symbol [11]. Instead of removing ISI completely, an MMSE equalizer allows some residual ISI in order to minimize the overall distortion. Thus MMSE is more robust [5] technique that directly minimizes the BER [6].

2.2 Spatial Diversity

In contrast to SM techniques, the spatial diversity techniques primarily aim to improve the error performance, which is accomplished on the basis of a diversity gain and a coding gain [2]. Thus MIMO channels can be exploited to achieve a full diversity order through space-time coding techniques, such as STBCs and STTCs [12]. Depending on which end of the wireless link is equipped with multiple antennas, the spatial diversity can be- Receive Diversity (*i.e.* single-input multiple-output (SIMO)) and transmit diversity (*i.e.* multiple-input single-output (MISO)). Receive diversity reduces the destructive and corrupting effects of fading due to multipath or interference from other users. In case of frequency-flat fading, an optimum combining technique *Maximum ratio combining* (MRC) can be used to maximize SNR at the combiner's output [3], which needs perfect channel knowledge at the receiver. However, with receiver MRC, most of the system complexity is concentrated at the receiver side (which is mobile station in wireless links) [13]. With *Selection diversity* (SD) [11], the received signal with the maximum instantaneous SNR is selected and all other received signals are discarded. To reduce the receiver complexity in terms of the number of RF chains, *Equal gain combining* (EGC) technique is used that brings all phases to a common point and combines them. The combined signal is the sum of the instantaneous fading envelopes of the individual branches.

Transmit Diversity techniques have been widely adopted in practice, as they reduce the processing complexity of the receiver [14]. *Space-Time Trellis Codes* (STTCs) are introduced as a high data rate, bandwidth and power efficient method of communication over wireless Rayleigh fading channels [15], that are based on the well defined trellis structures and thus they can be decoded using soft-decision decoding techniques at the receiver [8]. *Alamouti Space Time Coding* (STC) [12] sends the same data signals to both transmit antennas (1x2), but at different times, to improve the probability of successfully recovering the desired data [16]. *Orthogonal space-time block codes* (OSTBCs) constitute a generalization of Alamouti scheme to more than two transmit antennas. To construct full rate STBCs for complex modulation schemes, the strict constraint of perfect orthogonality is relaxed in favor of higher data rate and thus quasi-orthogonal STBCs typically offer reduced diversity gains compared to OSTBCs [2]. The basic configuration of a space-time coding scheme is illustrated in Figure 2.

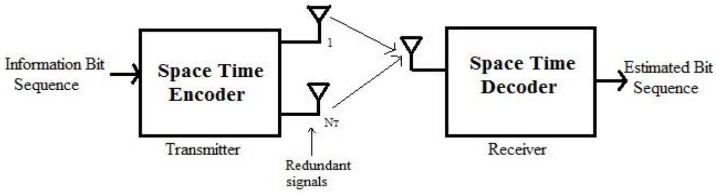

Figure 2. Basic Principle of Space-time Coding [15]

2.2 Beamforming

Multiple antennas can improve the SNR at the receiver and suppress co-channel interference (CCI) in a multiuser (MU) scenario. Both goals can be achieved by means of the beamforming techniques [2]. Beamforming uses multiple antennas to control the direction of a wavefront by appropriately weighting the magnitude and phase of individual antenna signals, also recognized as *Transmit Beamforming* [17]. Hence it provides better coverage to specific areas along the edges of cells. *Receive beamforming* makes it possible to determine the direction that the wavefront will arrive (direction of arrival (DoA)). It is also possible to suppress selected interfering signals by applying a beam pattern null in the direction of the interfering signal [17]. The basic principle of beamforming is illustrated in Figure 3, where, a beam former is employed both at the transmitter and the receiver side [2].

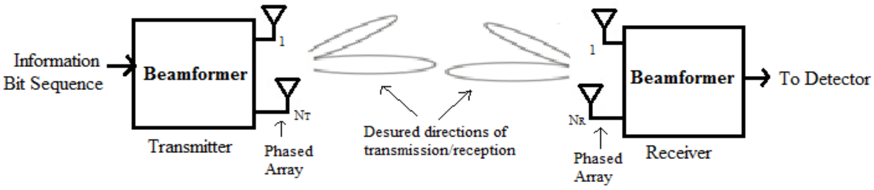

Figure 3. Basic Principle of Beam Forming [2]

Beamforming method can be applied in all antenna array systems as well as MIMO systems. Antenna technologies are divided into two groups, the Phased array systems with a finite number of fixed predefined patterns and Adaptive array systems (AAS) (adaptive beamforming) with an infinite number of patterns adjusted to the scenario in real time [1].

3. Channel Model

The multipath fading distribution is generally modeled with Rayleigh distribution, but when the fading is severe (NLOS), the Rayleigh model fall short to characterize the exact channel characteristics. Thus, a dominant model, named Nakagami-m model, is used to represent the channel. The major application of the Nakagami-m channel model is its versatility to state other random channel distributions. Assuming r is a Nakagami random variable, the corresponding pdf is described as [18]:

$$f_{Nakagami\text{-}m}(r) = \frac{2r^{2m-1}\Omega}{\Gamma(m)\Omega^{m}} e^{\frac{r^2}{\Omega}} \qquad (0 \le r < \infty) \qquad (1)$$

Here $\Gamma(\cdot)$ is the Gamma function, $\Omega = \frac{r^2}{m}$, r^2 is the average received signal power, and m is the inverse normalized variance, which satisfy the condition of $m \geq ½$, describing the fading severity [18]. The Nakagami-*m* channel model can also be used to approximate one-sided Gaussian distribution (m=1/2), Rayleigh distribution (m=1), Rician (m=2) and several other random distributions with the help of some appropriate one-to-one parameter mapping algorithms. When $m\rightarrow\infty$, the Nakagami-*m* distributed fading channel will converge to a non-fading additive white Gaussian noise (AWGN) channel [19]. Nakagami-*m* distributed fading channel exists in the literature for values of Nakagami-*m* parameter, m = 0.5 to 10. In addition the importance of Nakagami-*m* fading channel model is in the fact that is gives the widest span of the amount of fading (also called fading figure), among usual fading channel models.

4. Simulation Environment and Methodology

The error rate is an important parameter to characterize the performance behavior of wireless communication systems such as MIMO systems. BER is defined as the rate at which errors occur in a transmission system during a studied time interval. BER is a unit less quantity and is expressed as a 10 to the negative power in this paper. Noise and Quantization errors reduce the BER performance, through reconstruction of the digital waveforms. The precision of the analog modulation/ demodulation process and the effects of filtering on signal and noise bandwidth also influence quantization errors. Hence it is necessary for the system designers to evaluate the BER performance of different wireless systems. In this paper the error rate performance of signaling techniques through MIMO fading channels in different transmission modes, i.e. spatial multiplexing, spatial diversity and beam forming, is evaluated.

The spatial multiplexing techniques are analyzed with ZF and MMSE detection algorithms. To study the spatial diversity performances, the BER performance of MRC (receive diversity) is analyzed for QPSK. The performance of STTCs (transmit diversity) is simulated in a second order diversity (two transmit -one receive antennas) over Rayleigh fading channels (with Nakagami distribution factor, *m*=1). The specific cases of 4, 8, 16 and 32-State 4PSK (QPSK) codes are studied. Besides the BER of OSTBC codes is evaluate for QPSK modulation. The error probability for beamforming is also estimated and compared. The simulation methodology used for error rate analysis is represented in the Figure 4.

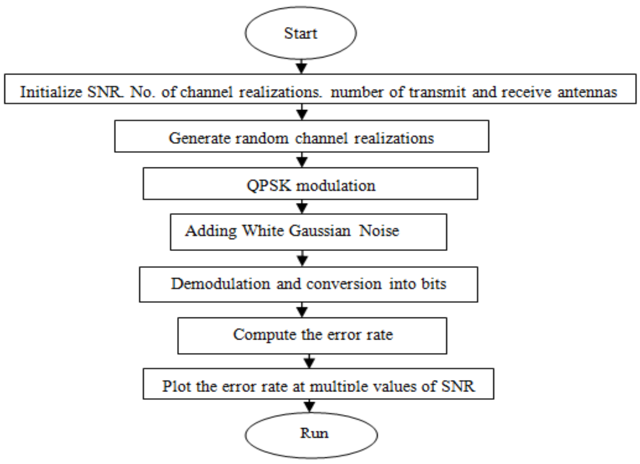

Figure 4. Flow Chart for the Computation of Error Rate

In this paper the Nakagami-*m* distribution is used because the signals do not travel in Line of sight (LOS). The Nakagami-*m* channel model represents the scattered signals that arrive at receiver via multiple paths. The Nakagami-m channel model is applicable for arbitrary values of the fading parameter *m*. The 'gamma distribution factor' or 'Nakagami-*m* parameter' used here for simulations is *m*=1 to 4. The BER v/s SNR curves are plotted logarithmic vertical scale by setting SNR along the x-axis and BER (or error probability) along the y-axis. The SNR is varied from 0 to 20dB, where, SNR is the ratio of the received signal power over the noise power in the frequency range of the process. SNR is inversely related to BER, means a high BER causes low SNR. The transmission employs QPSK modulation for all schemes. The simulation parameters used are described in Table 1.

Table 1. Simulation Parameters

Simulation Parameter		Value
SNR	SNR range in dB	0-20dB; 0-40dB
Modulation	Modulation technique used	QPSK
channel	Fading channel used	Nakagami-*m* fading channel (*m*=1, 2, 4)
N_T	Number of transmit antennas	4
N_R	Number of receive antennas	4
Antenna Configurations	SISO, MISO, MISO or MIMO format used	1x1; 1x2; 1x4; 2x1; 2x2, 4x4
Iterations	Number of channel realizations	20,000

5. Results and Discussions

In this section, the simulation results are presented for error rate analysis, which helps to characterize the behavior of different fading channels. The results acquired are as follows:

Figure 5 shows the outage probability analysis of ZF and MMSE equalization techniques under Nakagami-m fading channel, where Nakagami distribution factor m=1. Results indicate that the ZF equalizer gives better performance only in theoretical assumptions when noise is zero. However, its performance even worsens in mobile fading environments. Here N_T=N_R=4. To achieve the outage probability of 0.4 (for example), the SNR required at ZF receiver is 14dB and at MMSE receiver is 11dB with 2bits/transmission. Similarly, the SNR required for ZF and MMSE with 4bits/transmission is 21dB and 20dB respectively, to achieve outage probability of 0.4, however, at transmission rate =6, the SNR requirement at ZF and MMSE receivers is 27.1dB and 27dB. Hence, MMSE receiver results in around 3dB of improvement for transmission rate =2 and 1dB improvement for Rate=4, for 0.4 outage probability under Nakagami-m (m=1) fading channel, when compared with ZF receiver.

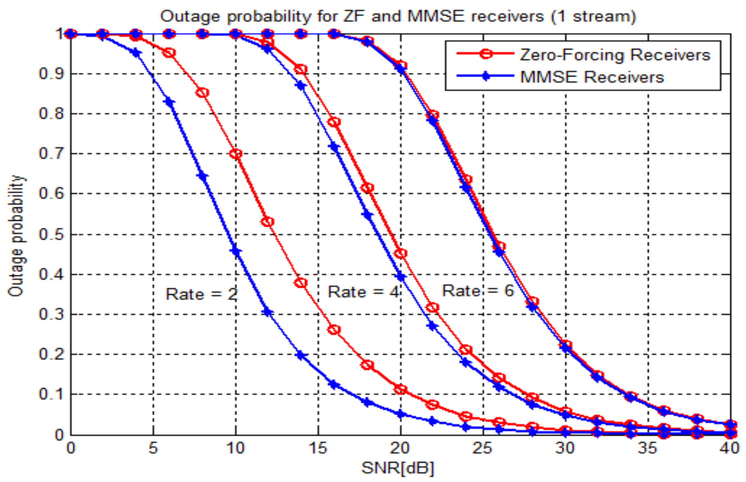

Figure 5. Outage Probability for ZF and MMSE Receivers under Rayleigh Fading Channel (*m*=1)

Figure 6 shows the outage probability analysis of ZF and MMSE equalization techniques under Nakagami-*m* fading channel, where *m*= 4. To achieve the outage probability of 0.4 (for example), the SNR required at ZF receiver for transmission rate 2, 4 and 6 bits/transmission, is 20dB, 27dB and 33dB, respectively. And at MMSE receiver, the SNR required to achieve the outage probability of 0.4, is 14dB, 25dB and

32.5dB, respectively, for transmission rate of 2, 4 and 6 bits/transmission. Hence, to achieve 0.4 outage probability, the MMSE receiver results in around a 6dB of improvement for transmission rate=2; around a 2dB improvement for Rate=4; and a 0.5dB improvement for the transmission rate=6, under Nakagami-*m* fading channel (*m*=4), when compared with ZF receiver.

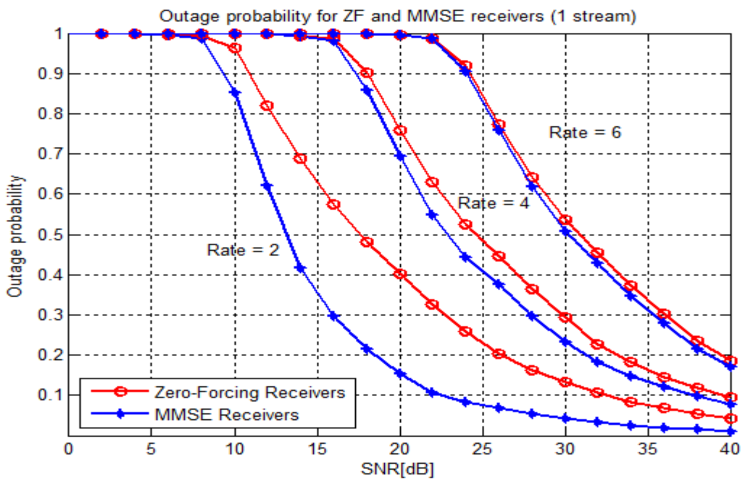

Figure 6. Outage Probability for ZF and MMSE Receivers under Nakagami-*m* Fading Channel (*m*=4)

The results obtained from above plots are summarized in Table 2. It indicates that to achieve the same outage probability, MMSE receivers show better performance in terms of outage probability.

Table 2. Comparison of ZF and MMSE Receivers to Achieve Outage Probability of 0.4

ZF-MMSE Receivers		ZF receiver	MMSE receiver
Nakagami-m Fading Channel (m=1)	Transmission rate = 2	14dB	11dB
	Transmission rate = 4	21dB	20dB
	Transmission rate = 6	27.1dB	27dB
Nakagami-m fading channel (m=4)	Transmission rate = 2	20dB	14dB
	Transmission rate = 4	27dB	25dB
	Transmission rate = 6	33dB	32.5dB

Figure 7 shows the BER performance of MRC scheme (receive diversity) with QPSK modulation technique and under Nakagami-*m* fading channel with *m*=1. The performance curve for the variation of BER with increasing SNR for 1x2 (one transmitting and two receive antennas) and 1x4 (one transmit antenna and four receive antennas), shows significant improvement in BER for given value of SNR as compared to no diversity SISO (1x1) scheme. The result specifies that the roll-off is steeper as the diversity order increases. At SNR of 8dB (for example), the BER of SISO is $10^{-1.8}$; the BER of MRC with (N_T =1 and N_R=2) is $10^{-2.5}$; and BER of MRC with (N_T=1 and N_R=4) is $10^{-3.9}$. It shows that the BER decreases with MRC methods and the performance is further improved with the number of receiving antennas. Moreover, the BER for all systems decreases monotonically with increase in SNR.

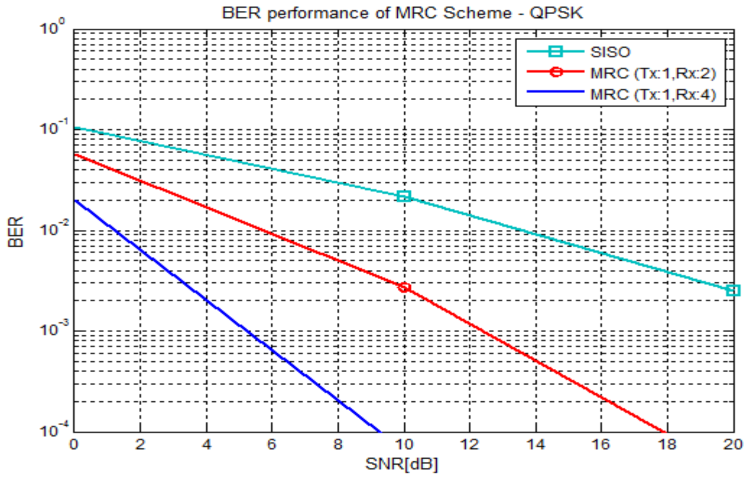

Figure 7. BER Performance of MRC Scheme

Figure 8 shows the BER performance of STTC QPSK (4-PSK) with different numbers of states (4, 8, 16 and 32), over 2x1 (two transmitter and one receiver antennas) Rayleigh channel (for m=1). As the number of states increases, the results shows better performance, as compared to other antenna diversity system, however the system complexity increases. An attractive point observed from Figure is that performance of these 4-states is comparable for very lower value for SNR (below 3 dB). At SNR of 16dB, BER of 4-state, 8-state, 16-state and 31-state STTCs is respectively, 10-1.95, 10-2.4, 10-2.5 and 10-2.7. It indicates that for 4PSK modulation, there is improvement as the number of states increases. Besides, the BER of STTC decreases as the SNR is increased.

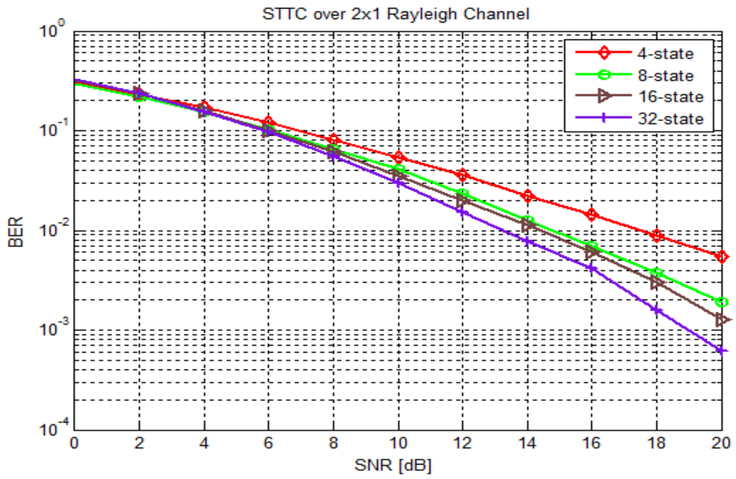

Figure 8. BER Performance Comparisons of QPSK STTC over 2x1 Rayleigh Channel

Figure 9 shows the BER performance of OSTBC and quasi-OSTBC, as compared to SISO under Nakagami- *m* fading channel with *m*=1. At SNR of 10dB, the BER of SISO is $10^{-1.7}$, the BER of quasi orthogonal STBC is $10^{-1.9}$ and the BER of OSTBC is 10^{-3}. It reveals that the BER of orthogonal are lower than the SISO systems. Also, the

BER performance of quasi-OSTBC is inferior to OSTBC. It indicates that quasi-OSTBC typically reduces the diversity gains as compared to OSTBC.

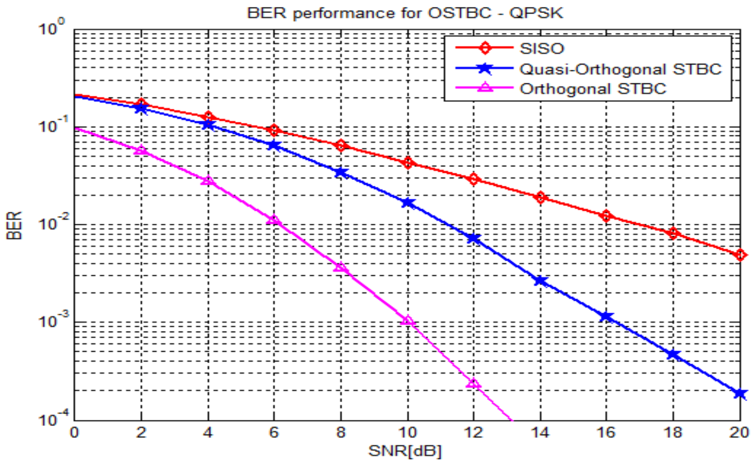

Figure 9. BER Performance of OSTBCs

To achieve a BER of 10^{-2}, the values of SNR required for various diversity techniques are tabulated here. The comparison results shows that to achieve the same BER, the receive diversity may improve performance but incorporating this type of diversity in receivers (mobile handsets) is undesirable due to the possible increase in power consumption, size, and cost. Therefore, in mobile wireless systems, diversity is employed mostly at the transmitter. The results in Table 3, are simulated for QPSK transmission and the maximum number of transmitting and receiving antennas used is 4 (M=4).

Table 2. Comparison of Various Diversity Techniques

Technique		BER achieved = 10^{-2}
MRC	MRC (Tx=1, Rx=2)	5.9 dB
	MRC (Tx=1, Rx=2)	1 dB
STTC	4-state	17.8 dB
	8-state	15 dB
	16-state	14.5 dB
	32-state	13.5 dB
OSTBC	Orthogonal STBC	6 dB
	Quasi Orthogonal STBC	11 dB

Figure 10 (a), (b) and (c) shows the error probability for QPSK transmission with beamforming technique for Nakagami-*m* fading channels, where *m*= 1, 2 and 4 respectively. An uncoded QPSK constellation is used for the transmission in each stream of eigenmode transmission with water-filling, where $N_T = N_R = 4$. The slope of the uncoded error curves indicated diversity gain achieved by each stream. The error probability estimation for different eigenmodes is compared with maximal eigenmode transmission and SISO/MISO systems.

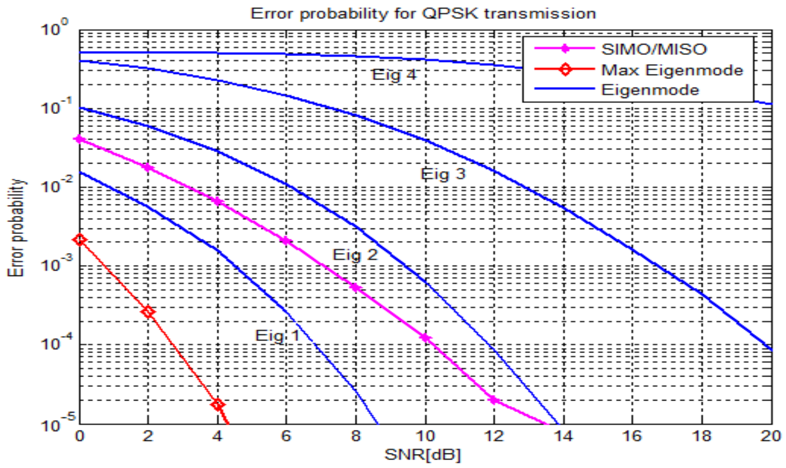

Figure 10 (a). Error Probability with Beamforming under Nakagami-*m* Fading Channel (*m* =1)

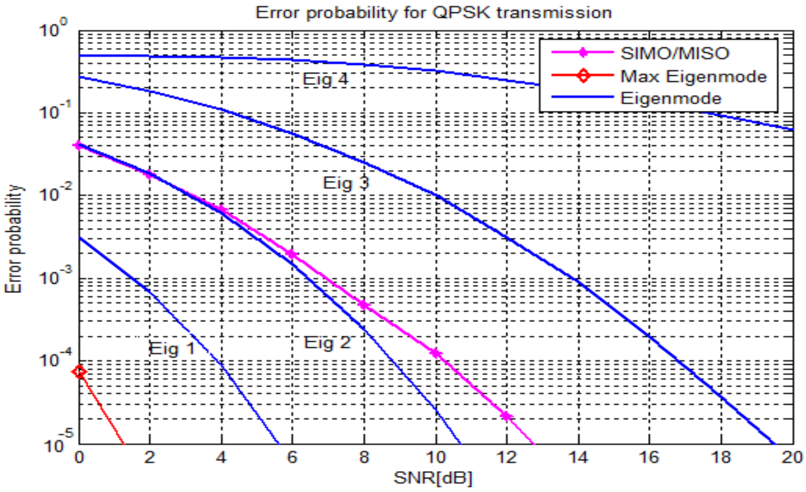

Figure 10 (b). Error Probability with Beamforming under Nakagami-*m* Fading Channel (*m* =2)

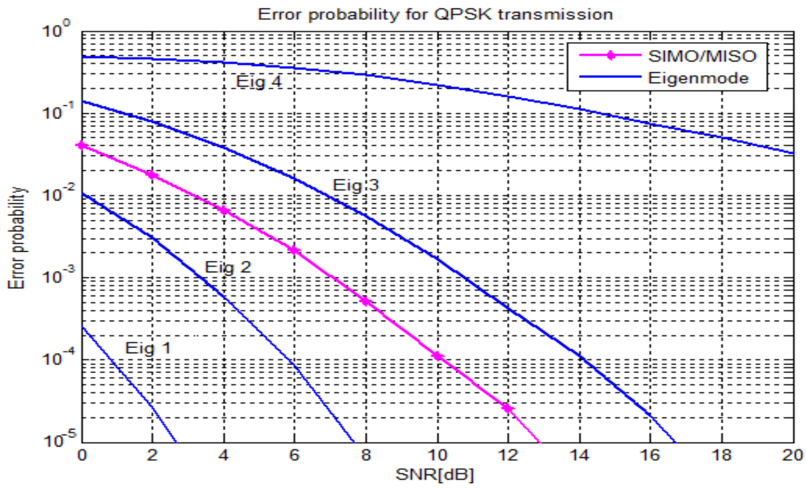

Figure 10 (c). Error Probability with Beamforming under Nakagami-*m* Fading Channel (*m* =4)

From the above results, it is found that the maximal eigenmode transmission outperforms the eigenmode transmission, under Nakagami-*m* fading channel, with different values of gamma or Nakagami distribution (*m* =1, 2, 4). The eigenmodes are also compared with SIMO/MISO systems, which are single stream systems. Results show that the error probability for eigenmodes 1, 2, 3 and 4; maximal eigenmode; and SIMO/MISO techniques. An improved performance can be obtained with Eig 1 and 2, and the error probability can be further improved by increasing the SNR. Moreover, on comparing the Figures 10(a), (b) and (c), it is revealed that the error probability is improved by increasing the value of Nakagami distribution factor '*m*'. For example, the error probability of maximal eigenmode (at very low SNR) is improved on increasing the value of *m* from 1 to 2, and for m=4, the error probability is negligibly small. For eigenmode2 (Eig 2), the error probability of 10^{-3} can be achieved at SNR of 9.5dB, 6.3dB and 3.4dB respectively, under Nakagami-*m* fading channel with *m*=1, 2 and 4. Similarly, for eigenmode 3 (Eig 3), the error probability of 10^{-3} can be achieved at SNR of 16.8dB, 13.8dB and 10.8dB respectively, under Nakagami-*m* fading channel with *m* =1, 2 and 4.

6. Conclusion

In this paper, the performance analysis and a comparative study is reported for Nakagami-*m* fading channels using Spatial Multiplexing, Spatial diversity (transmit and receive) and Beamforming technique. The BER and error probability is analyzed by varying the SNR. From the outage probability analysis of ZF and MMSE techniques, it is evident that the outage probability decreases for MMSE as compared to ZF receivers (for same transmission rates also). The error rate performances of various spatial diversity systems is investigated by using STTC, OSTBC and MRC schemes with QPSK modulation scheme. By using MRC techniques at the receiver, BER performance is improved and it gets better by increasing the number of receiver antennas. The BER performance of STTC indicates that a significant performance improvement can be achieved by increasing the number of transmit antennas or both transmitting and receiving antennas. The BER of OSTBCs is also improved as compared to single antenna systems. The error probability results for beamforming techniques are also improved on increasing the value of Nakagami distribution factor, *m*. The possible future work and research can be carried out for the cases of multiple receive antennas, higher order modulations, different types of fading channels, and imperfect channel estimation. Finally, the performance measurements in specific deployment conditions will be the key to evaluate precisely the overall benefits of MIMO systems in real-world wireless scenarios.

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