Channel capacity and bit error rate analysis in wireless communication system over Rayleigh fading channel

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Abstract: In high-speed wireless systems, bandwidth, transmit power, the complexity of hardware, quality of services, and throughput are the major issues. The 'Multi-Input-Multi-Output (MIMO)' system specifically works to increase the capacity of the wireless channel and to improve the 'Bit-Error-Rates (BER)' performance. The 'Orthogonal-Frequency-Division-Multiplexing (OFDM)' system is used for diminishing interferences within the available bandwidth. The spatial diversity of MIMO and the spectral efficiency of OFDM schemes can be combined to improve the channel capacity and error performance remarkably within the available bandwidth. Also, this combination provides robustness against various channel impairments. This article illustrates antenna diversity by employing different antenna configurations for the improvement in ergodic channel capacity. The 'Maximal-Ratio-Combing (MRC)' scheme provides receiver antenna diversity which enhances the channel capacity and improves the error rates performance of the MIMO-OFDM-based wireless communication system. Simulation results show that the proposed schemes achieve better results for channel capacity and error-rate performance.

Keywords: wireless communication; antenna; ergodic capacity; bit error rates; interference; fading channels; transmit and receive antennas.

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1 Introduction

In a wireless system, the signal is received in a set of several delayed copies of the originally transmitted signal through several paths with different amplitude and power, known as multipath fading. Multipath-fading in a wireless environment has a deleterious effect on the signal quality and the data rates or capacity. The MIMO antenna scheme is an effective technology to augment capacity or information rate with quality. MIMO scheme can be incorporated with several antennas at transmitter and receiver which provide antenna diversity. This leads to increased reliability and signal power as a result of diversity at receiver and transmitter (Paulraj et al., 2004; Goldsmith et al., 2003). Data rates or throughput of the MIMO-OFDM system can be increased by transmitting several signals in parallel using several antennas at the transmitter. This is known as spatial multiplexing since several parallel information streams are multiplexed in space rather than time or frequency (Duman and Ghrayeb, 2008; Cho et al., 2010). The diversity gain is necessary for adequate error performance and the spatial multiplexing provides high 'Spectral Efficiency (SE)' but limited diversity gain. Also, there is a trade-off between SE and diversity gain. So it is necessary to choose the proper algorithm to avoid this trade-off to achieve better error performance with considerable diversity gain (Duman and Ghrayeb, 2008). The concatenation of MIMO system with OFDM scheme referred to as MIMO-OFDM system efficiently fights against scarcity of bandwidth, power constraint, and various channel impairments and improves the data rates, QoS and trustworthiness of information over the wireless communication system.

Several researchers have worked in this area and the analysis of their findings is summarised in this section. Alamouti (1998) employed transmit diversity (Alamouti STBC scheme) with 2×1 and 2×2 antenna system and MRC scheme with 1×2 and 1×4 antenna system over BPSK modulation and Rayleigh fading channel. The simulation result for the MRC scheme shows the BER value of 1.9×10^{-3} and 6.0×10^{-3} for 1×2 and 1×4 antennas, respectively at the SNR of 10 dB. Alqahtani et al. (2019) proposed a rate-less STBC scheme using FPGA-based experimental setup, 2×2 antenna system, 64 subcarriers, 1000 symbols and shows that at 10% loss rate the error rate reduces to 0.625×10^{-4} for 8 RSTBC blocks using QPSK modulation over AWGN channel. Van Luong and Ko (2018) proposed an OFDM-IM (index modulation) scheme with MRC and greedy detector for the analysis of error rates. The authors use BPSK and QPSK modulation with single transmit and multiple antennas at receiver. The BER values for imperfect Channel State Information (CSI) with 1×2, 1×4 and 1×6 antenna system are found in the range of 10^{-2} to 10^{-5} over Rayleigh fading channel. Misra et al. (2017) proposed MRC and 'Equal Gain Combining (EGC)' schemes for the investigation of BER. Over Rayleigh fading channel using MRC scheme with 1×2 and 1×3 antenna system the BER values are found to be 1.7×10^{-3} and 1.4×10^{-4} and using EGC scheme for the same antenna system the BER values are 2.0×10^{-3} and 2.0×10^{-4} at 10 dB SNR. Das and Subar (2017) proposed the MRC scheme over 'Two-Wave Diffuse Power (TWDP)' fading channels in the MIMO system for BER analysis. Authors use M-QAmodulation with 1×2 and 1×3 antenna stems for error rate analysis. The simulation results show e BER values of 6.5×10^{-4} and 3.5×10^{-5}, respectively at 10 dB SNR. Nandi et al. (2017) theoretically shown that the error rates are comparable and in the range of 10^{-3} to 10^{-4} at 10 dB SNR for the Alamouti scheme with 2×1 and MRCche with 1×2 antenna system. Dlodlo et al. (2018) employed differential STBC with trellis coding over Rayleigh fading channel for BER analysis and found the BER value of 4.0×10^{-2} at the SNR of 10 dB. Lee (2018) employed the MRC scheme over imperfect CSI to examine the ergodic capacity and outage capacity in a MIMO system. The ergodic capacity for one and two users is found to be 3.7 bits/s/Hz and 4.25 bits/s/Hz, respectively. The outage capacity for 10% outage is 2.5 bits/s/Hz and 3.3 bits/s/Hz and the outage probability is of 6.5×10^{-2} and 4×10^{-3} for one and two users, respectively. Kundu and Hughes (2017) considered Uniform Circular Array (UCA) and the Uniform Linear Array (ULA) for 64 subcarriers in MIMO-OFDM broadband system using 2×2 and 4×4 antenna system and observed *t* capacity and outage capacity in the range of 4.5 to 8.0 bits/s/Hz and 4.4 to 7.8 bits/s/Hz, respectively. Sahoo and Sahoo (2019) used the MIMO channel model with 'Diffusion Least-Mean-Square (DLMS) algorithm, 2×2 antenna configuration, 16 QAM modulation, AWGN channel and STBC code diversity scheme for the investigation of channel capacity over IEEE802.11, I-METRA and 3 Gpp channels. The simulation result shows that the capacity is 9.9, 6.0 and 8.5 bits/s/Hz, respectively for above listed channel models.

From the above literature review and analysis, it is observed that the MRC scheme employed by Alamouti (1998) and Alqahtani et al. (2019) over the AWGN channel reduces BER up to the value of 10^{-4}. On the other hand, over Rayleigh fading channel the MRC scheme employed by Van Luong and Ko (2018); Misra et al. (2017) and Das and Subadar (2017), reduces BER in the range from 10^{-4} to 10^{-5}. All the above authors have used 1×2 and 1×4 or 1×6 antenna systems for the BER reduction. The MRC scheme employed by Lee (2018) and multiple antenna configuration techniques by Kundu and Hughes (2017); and Sahu and Sahu (2019) provided ergodic channel capacity of 3.7 bit/s/Hz to 9.9 bit/s/Hz and achieved outage capacity in the range of 2.5 bit/s/Hz to 7.8 bit/s/Hz with incomplete CSI on the AWGN channel.

This article mainly focuses on improving the error rate and channel capacity of the MIMO-OFDM system using antenna diversity $(M_T \times M_R)$ and MRC $(1\times M_R)$ schemes. For capacity analysis in the proposed MIMO-OFDM systems, Singular Value Decomposition (SVD) for channel matrix approximation and water filling algorithms are employed for simulation. For the error rate analysis, the MRC scheme with $(1\times M_R)$ where M_R= 2 or 4, has been employed and their performance compared with the results of the 'Equal Gain Combining (EGC)' scheme and 'Selection Combining (SC)' scheme. Also, the error rate for a simple receive diversity scheme has been analysed and compared with MRC, SC, and EGC schemes.

This article is organised into seven sections as follows: Section 2 gives a brief introduction to the OFDM system, a brief introduction to the MIMO system and illustrates the function of the basic MIMO OFDM system. Section 3 provides basic knowledge about the antenna diversity technique. In addition, this section describes the MRC scheme and provides the mathematical derivation for maximum SNR and the error rates. Section 4 gives brief knowledge about the Rayleigh fading channel. Also, it provides mathematical derivation for average error probability over Rayleigh fading channel. Section 5 describes an ergodic capacity as well as outage capacity in brief. Section 6 describes a detailed analysis of the simulation results. And finally, Section 7 illustrates the conclusion of the research article.

2 System model

In this section, the proposed system for wireless communication is illustrated. The proposed model consists of concatenation of MIMO and OFDM system.

2.1 OFDM system

The OFDM is a leading technology that provides strength against various impairments caused due to multipath fading. It has good spectral efficiency which reduces the requirement of additional bandwidth (Alqahtani et al., 2019). Owing to the orthogonal spacing of subcarriers, the OFDM system becomes less sensitive to 'Inter-Symbol Interference (ISI)'. The main drawback of the OFDM system is that its performance is badly affected due to the presence of high 'Peak to Average-Power-Ratio (PAPR)' in the OFDM signal. The high peaks in OFDM symbols may break the orthogonality of the OFDM system which causes the OFDM system to become more susceptible to 'Inter-Carrier Interference (ICI)' (Rateb and Labana, 2019; Gökceli et al., 2019). An attempt to reduce PAPR affects the error rate performance of the system which results in loss of reliability of wireless communication. Hence it is obligatory to diminish the PAPR without affecting the BER performance of the MIMO-OFDM-based wireless communication system. The BER performance of the OFDM system in AWGN and Rayleigh fading channel is analysed in the result section and depicted in Figure 4. It is observed that over the Rayleigh channel the BER decreases linearly with increasing SNR, whereas over the AWGN channel the BER graph falls exponentially and after a certain value of SNR the error rate observes a sharp drop. More detail about the OFDM transmitter and receiver is described in Sub-section 2.3.

2.2 MIMO system

As discussed in earlier sections the MIMO antenna scheme specifically provides antenna diversity which leads to enhanced information rates or channel capacity and improves BER performance. The MIMO antenna scheme using (MR) receives and (MT) transmit antenna is presented in Figure 1. The MIMO $\left(M\_T \times M\_R\right)$ antenna configuration provides spatial diversity. It is a powerful technique of fighting the harmful fading effects (Cho et al., 2010). The primary benefit of antenna diversity is to fight against a multipath fading environment. Each receive antenna receives multiple copies of transmitted signals from M_T transmitting antennas. Each copy of the transmitted signal experiences different channel fading effects. Thus, one or more receive antennas may receive a better quality signal without any interference and this way reliability is maintained (Zaidi et al., 2018). For the MIMO system shown in Figure 1, if 'H' is channel matrix of 'M_T' transmitting and 'M_R' receiving antennas ($M_T \times M_R$ matrix) then the MIMO system model is given by

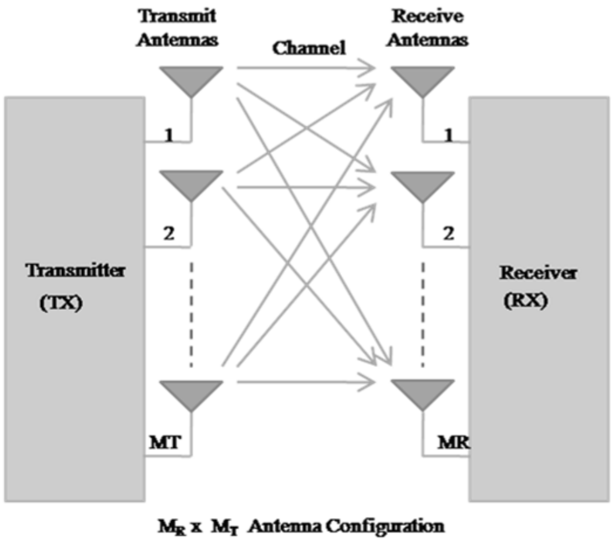
$$\hat{Y} = H\hat{S} + \hat{n} \tag{1}$$

where

$$H = \begin{bmatrix} h_{11} h_{12} \text{-----} h_{1M_r} \\ h_{21} h_{22} \text{-----} h_{2M_r} \\ - \\ - \\ h_{M_{t1}} h_{M_{t2}} \text{---} h_{M_t M_r} \end{bmatrix}$$

and $\hat{Y}$ is output vecr, H represents the channel matrix $\left(M_T \times M_R\right)$, $\hat{S}$ is the transmitted symbol vector and $\hat{n}$ is the noise vector where each elements of noise are inpendently and identically distributed (iid).

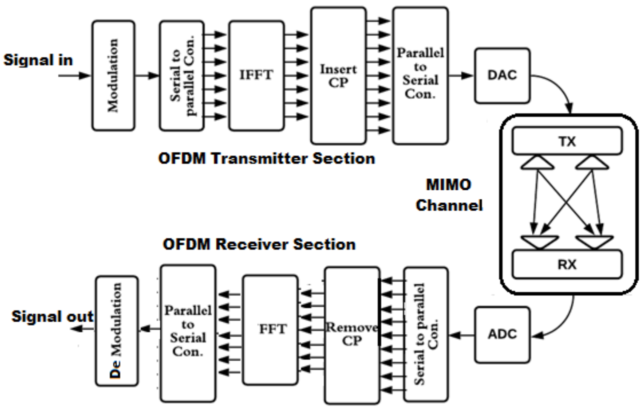
Figure 1 MIMO antenna system $\left(M_T \times M_R\right)$



2.3 MIMO-OFDM system

In the introduction section, many advantages of the MIMO-OFDM system have been discussed. In addition to that, the MIMO-OFDM system is also capable of fighting against frequency selective fading and thus the use of complex equalisers is prohibited (Alqahtani et al., 2019). The basic MIMO-OFDM model is portrayed in Figure 2. The modulated signal using any of the constellation techniques is complex which is converted into parallel form. The parallel output data stream is given to the input of *N* point IFFT. At *N*-point IFFT the parallel data is divided into *N* parallel symbols and transmitted via *N* sub-carriers. The IFFT output is arranged in several blocks and the guard signal or 'Cyclic Prefix (CP)' is inserted in each block. Inserting CP in each data block minimises ISI. After inserting the guard signal the output of the CP block is again converted into serial form and then using serial 'Digital to Analogue Converter (DAC)' the signal is transformed into analog form. Now in the time domain, this analogue signal is transmitted through the wireless channel (Cho et al., 2010). The receiver section functions exactly opposite to transmission section. Here, CP is removed from each block and the original signal is obtained after demodulation.

Figure 2 Basic MIMO-OFDM system



3 MIMO diversity techniques

Multipath propagation of the signal in the wireless environment leads to destructive interference thus received signal power falls below the noise power which is known as deep fade. In such case, the system performance is seriously degraded. To get rid of such a situation we need to use diversity schemes at the receiver or transmitter or both in the MIMO system. Multiple transmit and receive antennas in the MIMO system provide multiple copies of the signal transmitted over more than one link in space; this is referred to as spatial diversity. In this case, even if one or more links are in the deep fade, a good quality signal can be obtained successfully through the remaining links. Therefore, employing spatial diversity in the MIMO antenna system will significantly increase systems performance (Kang and Alouini, 2003). Various schemes can be used for providing spatial diversity in the MIMO system, for example; 'Space-Time Coding (STC)', Alamouti STBC, 'Beamforming (BF)' and 'Maximum Ratio Combining (MRC)'. These techniques employ CSI at the receiver or transmitter. The CSI at the transmitter end is obtained via feedback from the receiver. BF and MRC have an advantage over STC and provide full diversity gain. BF/MRC scheme allows us to use different antenna congratulations to provide additional gain (Ahn et al., 2009).

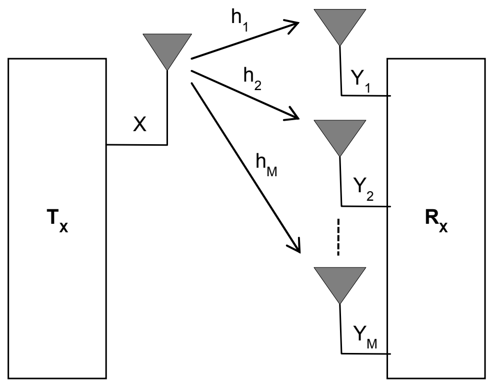
3.1 Maximal ratio combining (MRC)

There are many techniques included in MRC schemes such as 'Selection Combining (SC)', 'Equal-Gain Combining (EGC)' and 'Switch-and-Stay Combining (SSC)' available for combining received signals via different wireless links or diversity links (Duman and Ghrayeb, 2008). The Alamouti scheme employs diversity at the transmitter whereas the MRC scheme uses diversity at the receiver. In the MRC at the receiver, the signals received through all diversity links are co-phased, weighted proportionally, and then combined (Das and Subadar, 2017; Tiwari and Saini, 2014). Although the MIMO-MRC is one of the best methods for maximising the SNR, it is significantly affected by 'Co-Channel Interference (CCI)' (Kang and Alouini, 2003; Ahn et al., 2009; Tiwari and Saini, 2014).

3.1.1 Maximum SNR at MRC receiver

The MIMO system with MRC scheme consisting of one transmit and M number of receive antennas is presented in Figure 3. If $h_1, h_2, \ldots, h_M$ are the channel coefficients for M links, x is signal input, and $y_1, y_2, \ldots, y_M$ is the output signal.

Figure 3 MIMO antenna system with $(1 \times M)$ antennas configuration



The system model for MIMO is written as

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_M \end{bmatrix} x + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_M \end{bmatrix}$$

$$\bar{y} = \bar{h}\, x + \bar{n} \tag{2}$$

where $\bar{y}$ is received vector $(1 \times M_R)$, $\bar{h}$ is channel vector $(1 \times M_R)$, $\bar{n}$ is a noise vector $(1 \times M_R)$, and x is transmitted signal. The expected value of noise power or variance at each receive antenna is $E\{|n_i|^2\} = \sigma^2$, $i = 1, 2, \ldots, M$. Assuming $E\{|n_i n_j|\} = 0$ for $i \neq j$, and noise at any pair of antennais uncorrelated. Now combining received signals linearly at the receiver using combining weights w_n, where $n = 1, 2, \ldots, M$, we have

$$y^{\sim} = w_1^* y_1 + w_2^* y_2 + w_3^* y_3 + .. + w_M^* y_M \tag{3}$$

Since $\left[w_1^*, w_2^*, w_3^*, \ldots, w_M^*\right]\left[y_1, y_2, \ldots, y_M\right]^T = \bar{w}^H \bar{y}$ which is beamforming output. Where $\bar{w}$ is a beamforming vector $\left[w_1, w_2, \ldots, w_M\right]^T$. So beamforming output is $\bar{w}^H \bar{y} = \bar{w}^H \left(\bar{h}\, x + \bar{n}\right)$

$$\bar{w}^H \bar{y} = \bar{w}^H \bar{h}\, x + \bar{w}^H \bar{n} \tag{4}$$

where $\bar{w}^H \bar{h} x$ is a signal component and $\bar{w}^H \bar{n}$ is a noise component. The signal power equals to $\left|\bar{w}^H \bar{h}\right|^2 p$ and the noise power is $\sigma^2 \bar{w}^H \bar{w}$, so we have SNR with MRC

$$SNR_{MRC} = \frac{\left|\bar{w}^H \bar{h}\right|^2 p}{\sigma^2 \bar{w}^H \bar{w}} \tag{5}$$

Choose $\bar{w}$ such that $\bar{w}^2 = \left|\bar{w}^H \bar{w}\right| = 1$, so now SNR is

$$SNR_{MRC} = \frac{\left|\bar{w}^H \bar{h}\right|^2 p}{\sigma^2} \tag{6}$$

For the maximum Signal to Noise Ratio (SNR), we can choose MRC as

$$\bar{w}_{opt} = \frac{\bar{h}}{\bar{h}} = \frac{1}{h}\left[h_1, h_2, ..., h_M\right]^T \tag{7}$$

Further expanding equation for SNR at MRC is

$$SNR_{MRC} = \frac{h^2 p}{\sigma^2} \tag{8}$$

3.1.2 Bit error rate (BER) of MRC at receiver

Let $g = h^2 = \left(|h_1|^2 + |h_2|^2 \cdots |h_M|^2\right)$, is a chi-square random variable with a 2 M degree of freedom. Now, the distribution of gain (pdf)

$$F_G(g) = \frac{1}{(M-1)!} g^{M-1} e^{-g} \tag{9}$$

Therefore, SNR at receiver

$$SNR_{MRC} = \frac{gp}{\sigma^2} \tag{10}$$

$$SNR_{MRC} = g.SNR \tag{11}$$

Now, a Bit Error Rate (BER) is given by

$$BER = Q\sqrt{SNR} = Q\sqrt{g.SNR} \tag{12}$$

where 'g' is the random variable, so averaging above expression for 'g' to derive the average BER.

$$\text{Average BER} = \int_0^\infty Q\left(\sqrt{g.SNR}\right) F_G(g)\, dg \tag{13}$$

$$= \int_0^\infty Q\left(\sqrt{g.SNR}\right) \frac{1}{(M-1)!} g^{M-1} e^{-g}\, dg \tag{14}$$

Above expression is simplified as

$$\text{Average BER} = \left(\frac{1-\lambda}{2}\right)^M \sum_{m=0}^{M-1} \begin{pmatrix} M+m-1 \\ C \\ m \end{pmatrix} \left(\frac{1+\lambda}{2}\right)^m$$
$$= \left(\frac{1-\lambda}{2}\right)^M \sum_{m=0}^{M-1} \begin{pmatrix} M+m-1 \\ C \\ m \end{pmatrix} \left(\frac{1+\lambda}{2}\right)^m \tag{15}$$

This gives the expression for average BER, where, $\lambda = \sqrt{\frac{SNR}{2+SNR}}$, for high SNR

$$\frac{1}{2}(1-\lambda) = \frac{1}{2}\left(1-\sqrt{\frac{SNR}{2+SNR}}\right) \tag{16}$$

$$= \frac{1}{2}\left[1-\left(\frac{1}{1+2/SNR}\right)^{1/2}\right]$$

$$\approx \frac{1}{2}\left[1-\left(1-\frac{1}{2}\frac{2}{SNR}\right)\right]$$

$$\approx \frac{1}{2SNR} \tag{17}$$

Similarly, $\frac{1}{2}(1+\lambda) \approx 1$, substituting in the equation of average BER, we have BER expression for M receive antennas after MRC at high SNR

$$BER_{MRC} = \begin{matrix} 2M-1 \\ C \\ M \end{matrix} \frac{1}{2^M}\left(\frac{1}{SNR}\right)^M \tag{18}$$

4 Rayleigh fading channel

In multipath fading situation, the channel is said to be Rayleigh fading channel if the coefficient of channel has zero mean. In this case, the gain of the channel is a Rayleigh random variable. If h denotes channel gain which is complex random variable on $(0 \text{ to} 2\pi)$ and $|h|$ denotes absolute channel gain with $(\angle h)$ phase angle φ, then the p.d.f. of $|h|$ is

$$f_{|h|}(u) = 2u/P_a \, exp\left(-u^2/P_a\right), \text{ if } u > 0 \tag{19}$$

where P_a is the average power of the channel (Duman and Ghrayeb, 2008 ; Gómez-Déniz et al., 2019).

To determine the average error probabilities over Rayleigh fading channels for a given channel coefficients of h, the instantaneous BER scaled by $|h|^2$ is given by

$$P_b(h) = Q\left(\sqrt{2|h|^2 SNR}\right) \tag{20}$$

Then, the average BER over Rayleigh fading channel using BPSK modulation is

$$P_b = E_h\left[P_b(h)\right] \tag{21}$$

$$P_b = \int_0^\infty Q\left(\sqrt{2uSNR}\right) e^{-u}\, du \tag{22}$$

Solving integration in equation (22) by parts we have

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{1+SNR}}\right) \tag{23}$$

For SNR >> 1, the above expression can be approximated as

$$P_b \approx \frac{1}{4SNR} \tag{24}$$

From the above equation of average BER, it is clear that the probability of error over the Rayleigh fading channel decreases at higher SNR values. This is unlike the error probability for the AWGN channel where it decreases exponentially with SNR (Duman and Ghrayeb, 2008). For any modulation schemes, the BER decreases slowly with an increase in SNR over Rayleigh fading channel. Whereas over the AWGN channel the error rates fall exponentially and after a certain value of SNR the error rates fall with a sharp drop.

5 MIMO channel capacity

The capacity for the AWGN channel was first defined by Shannon in 1948. The maximum information rate per unit time with minimum error achieved by the wireless channel is the capacity of the wireless channels. Different types of antenna configurations are; a) 'Single Input Single Output (SISO)' b) 'Single Input Multiple Outputs (SIMO)' c) 'Multiple Input Single-Output (MISO)' and d) 'Multiple Input Multiple-Output (MIMO)'. The channel capacity 'C' for SISO, SIMO, MISO and MIMO is given by (25) to (28), respectively (Sarangi and Datta, 2018).

$$C = B\,log_2\left(1 + S/N\right) \tag{25}$$

$$C = M_R\,B\,log_2\left(1 + S/N\right) \tag{26}$$

$$C = M_T\,B\,log_2\left(1 + S/N\right) \tag{27}$$

$$C = M_T\,M_R\,B\,log_2\left(1 + S/N\right) \tag{28}$$

where *B* represents the bandwidth and S/N represents SNR, M_T and M_R are the numbers of transmitting and receiving antennas respectively. Conventionally, for the study of MIMO capacity, two types of capacity definitions are employed, namely Shannon (ergodic) capacity and non-ergodic or outage capacity.

5.1 Ergodic channel capacity (Shannon capacity)

The expected value of channel capacity of the 'Additive White Gaussian Noise (AWGN)' channel is referred to as ergodic or Shannon capacity. Consider a random channel matrix 'H' which is ergodic. Here, let's assume 'Channel State Information (CSI)' that is the channel knowledge is accessible at only receiver and signals are complex Gaussian, equally powered and independent at the transmitter. Therefore taking an expectation over '*H*', the ergodic channel capacity for MIMO channel is

$$C = E\left\{\log_2\left[det\left(I_{M_R} + \frac{E_s}{M_T N_0}.HH^H\right)\right]\right\} \tag{29}$$

The CSI observed at the receiver is classified according to channel coefficients realisations. The individual capacity is computed for each realisation since inputs are still independent Gaussian. Finally, overall capacity is computed by taking an average of all the values (Duman and Ghrayeb, 2008; Choudhury and Gibson, 2007; Chen, 2012).

5.2 Non-ergodic channel capacity

For the non-ergodic channels, fading coefficients remain invariable over the length of the codeword. Here, Shannon capacity is simply zero since the probability of the shared information between input and output is less than given information rate *R* is non-zero. So in such a condition instead of ergodic capacity we should define another type of capacity that is outage capacity. In this scenario for low SNR, it is not suggested to allocate power equally between all transmit antennas. Because in this situation it is a very tedious job to categorise real signals and noise. Hence, it is suggested that instead of considering all transmit antennas, we should manage them into smaller subset with independent Gaussian input and allocate high power to these subsets (Telatar, 1999; Duman and Ghraye, 2008 ; Choudry and Gibson, 2007; Ahmad et al., 2013). Assuming '*k*' transmit antennas $\left(k \le M_T\right)$ and independent Gaussian input with *k*/2 variance are used. For a given SNR (ρ) the capacity is given by

$$C(\rho) = \log.\det\left(I_{M_R} + \rho H^H R_x(k) H\right) \tag{30}$$

where $R_x(k) = \frac{1}{k}\text{diag}\{1,1,\ldots,1,0,0,\ldots..0\}$. Therefore, the outage probability for given transmission rate *R* is

$$P_{out} = \min_{k=1,2,.M_T} P\left(\log.\det\left(I_{M_R} + \rho H^H R_x(k) H\right) \le R\right) \tag{31}$$

6 Result and discussion

As stated earlier, this article mainly focuses on the analysis of error rate performance and channel capacity of MIMO-OFDM system. This section analyses channel capacity and error rate performance of the MIMO-OFDM system. Here, the channel capacity is analysed on Simple Antenna Diversity $\left(M_T \times M_R\right)$ system and Receiver Antenna Diversity $\left(1 \times M_R\right)$ system on AWGN channel. Additionally, this section demonstrates the BER performance of the MIMO system; including simple receive diversity over the AWGN channel. And the result is mainly compared with the BER performance of the MRC system on the Rayleigh feeding channel. The BER results on both the channels show that the AWGN channel gives very good BER performance even at low SNR values, whereas the Rayleigh fading channel requires more than double the SNR value to get the same BER result. This is because the BER graph on the AWGN channel drops exponentially and rapidly and after a certain amount of SNR, there is a sharp drop in the BER graph. Whereas it is observed that the BER graph on Rayleigh fading channel is linear as compared to AWGN channel and drops slowly. This BER performance of MIMO-OFDM system on AWGN channel and Rayleigh fading channel is shown in Figure 4. It is seen from Table 1 that to achieve a BER of 10^{-3}, the AWGN channel requires only 6.8 dB of SNR, while the Rayleigh fading channel requires an SNR of 24 dB. Thus, there is an SNR loss of 17.2 dB from the Rayleigh fading channel. Furthermore, on the Rayleigh fading channel, the SNR loss increases rapidly when a better value of BER is further attempted.

Figure 4 BER vs. SNR comparisons for AWGN and Rayleigh fading channel

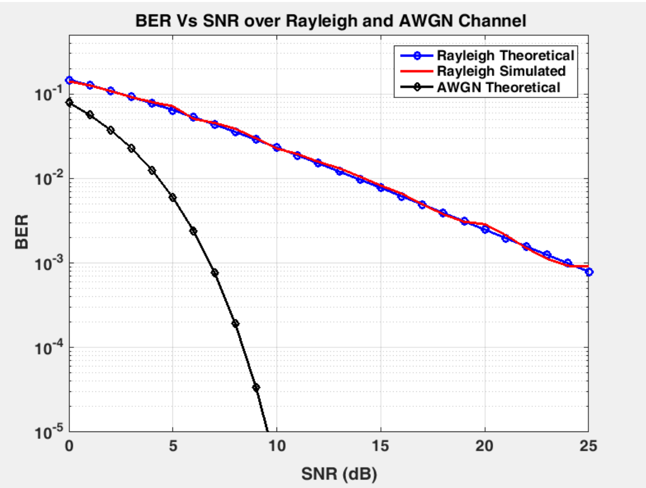
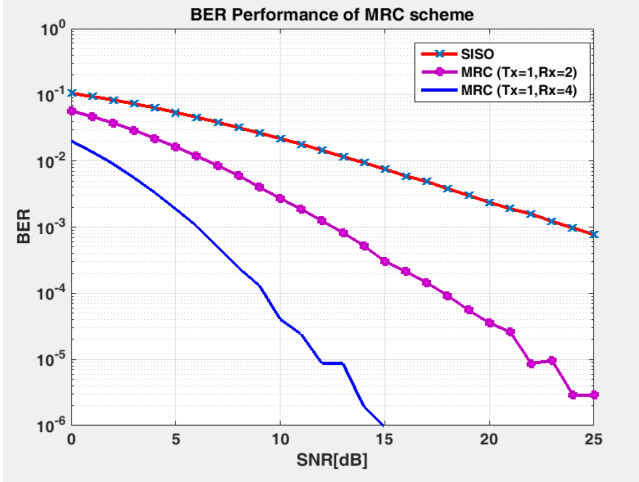


Table 1 BER performance comparison for AWGN and Rayleigh fading channel

BER Value	*SNR (dB) value for Channel*		*SNR loss for Rayleigh fading channel*
	AWGN	*Rayleigh*	
10^{-2}	4.4 dB	14 dB	9.6 dB
10^{-3}	6.8 dB	24 dB	17.2 dB
10^{-4}	8.3 dB	34 dB	25.7 dB
10^{-5}	9.5 dB	44 dB	34.5 dB

Over Rayleigh fading channel, the BER versus SNR performance of MRC schemes with (1×2) and (1×4) antenna configuration is depicted in Figure 5. From the Figure 5 it is clear that at the BER value of 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6}, the MRC scheme with (1×4) antenna configuration yields SNR gains of 6.0 dB, 9.0 dB, 11.8 dB and 14.9 dB, respectively, compared to MRC scheme with (1×2) antenna configuration where the same values of error rates obtained at the SNR of 12.6 dB, 17.7 dB, 22 dB and 27.5 dB, respectively. It has been observed that on the Rayleigh fading channel, the MRC scheme performs better for error reduction with a (1×4) antenna system, but at the cost of hardware complexity and higher power consumption due to a greater number of antennas at the receiver.

Figure 5 Error rate performance comparisons of MRC schemes

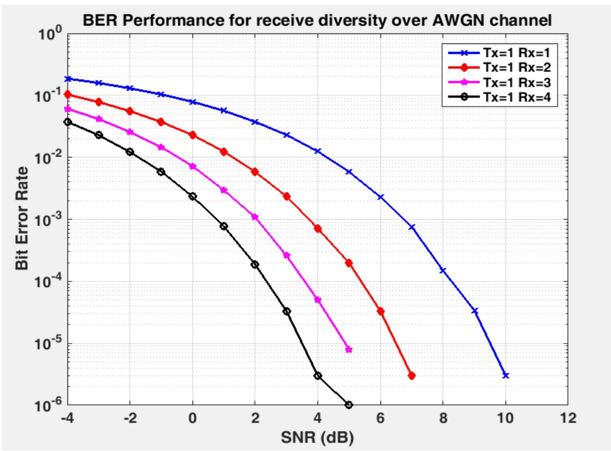


The BER performance of SISO, MRC (1×2), and MRC (1×4) schemes at different values of SNR is shown in Table 2. It is observed that after an SNR of 10 dB on the Rayleigh fading channel, the MRC (1×4) scheme yields an error rate similar to the error rate on the AWGN channel. And this is proved by the BER results of a simple receiving diversity scheme on the AWGN channel as shown in Figure 6 where a receive diversity scheme with one transmitting antenna and two to four receiving antennas are employed for simulation on the AWGN channel.

Table 2 BER performance comparison for MRC scheme

SNR (dB)	*BER value for*		
	SISO (1 × 1)	*MRC (1 × 2)*	*MRC (1 × 4)*
10 dB	2.1×10^{-2}	2.8×10^{-3}	4.0×10^{-5}
15 dB	8.0×10^{-3}	3.0×10^{-4}	9.0×10^{-7}
20 dB	2.5×10^{-3}	3.5×10^{-5}	Approx. 10^{-7}
25 dB	8.0×10^{-4}	3.0×10^{-6}	Approx. 10^{-8}

Figure 6 Error rate performance of receive diversity scheme over AWGN channel

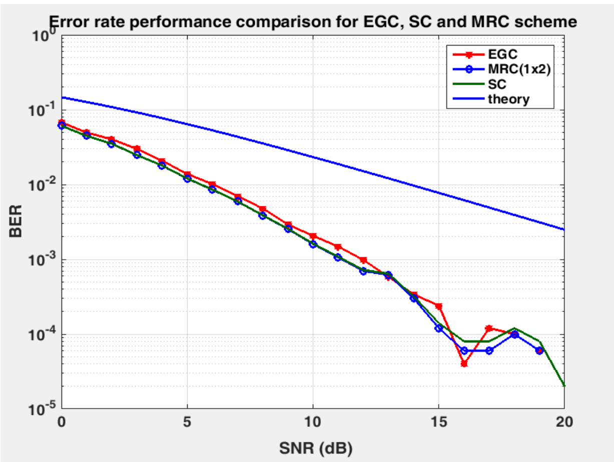


The above simulation is done using BPSK modulation, 10^6 number of bits per symbol, and hard decision coding at the receiver. Table 3 shows the error rate comparison for $(1\times M_R)$ diversity scheme, where M_R = 2, 3 and 4 receive antennas. Figure 7 shows the error rate performance on a Rayleigh fading channel with the same gain combination (EGC), Selection Combination (SC) and MRC scheme (1×2) antenna configuration.

Table 3 Error rate comparisons for receive diversity scheme $(1\times M_R)$

SNR (dB)	*BER value for receive diversity using*		
	(1×2)	*(1×3)*	*(1×4)*
4 dB	8.0×10^{-4}	4.5×10^{-5}	4.0×10^{-6}
6 dB	3.0×10^{-5}	$BER \ll 10^{-6}$.	$BER \ll 10^{-7}$.
8 dB	1.0×10^{-6}	$BER \ll 10^{-7}$	$BER \ll 10^{-7}$.
10 dB	1.0×10^{-7}	$BER \ll 10^{-7}$	$BER \ll 10^{-7}$

Figure 7 Error rate performance comparisons for EGC, SC and MRC scheme



The above simulation is done using BPSK modulation, 10^6 number of bits per symbol, and hard decision coding at the receiver. Table 3 shows the error rate comparison for $(1\times M_R)$ diversity scheme, where M_R = 2, 3 and 4 receive antennas. Figure 7 shows the error rate performance on a Rayleigh fading channel with the same gain combination (EGC), Selection Combination (SC) and MRC scheme (1×2) antenna configuration. The result shows that the error rate performance is comparable for all three plans. An error rate of 10^{-3} is achieved for MRC and SC at an SNR of 11 dB, while the same error rate is achieved at 12 dB for the EGC scheme. The error rates for EGC, SC and MRC at 16 dB SNR are found to be 4.0×10^{-5}, 8.0×10^{-5} and 6.0×10^{-5}, respectively. The ergodic channel capacity of the MIMO $(M_T\times M_R)$ system is illustrated in Figure 8. For simulation, 1 to 4 transmitting and 1 to 5 receiving antennas, water filling algorithm, Singular-Value Decomposition (SVD) for channel matrix approximation are used. This simulation is done on the AWGN channel using 10^4 iterations. A demonstration of the channel capacity for different combinations of transmitting and receivingntennas is shown in Figure 8. The channel capacity at SNR values of 10 dB to 30 dB for different channel combinations is shown in Table 4.

Figure 8 Ergodic channel capacity for different antenna configuratio

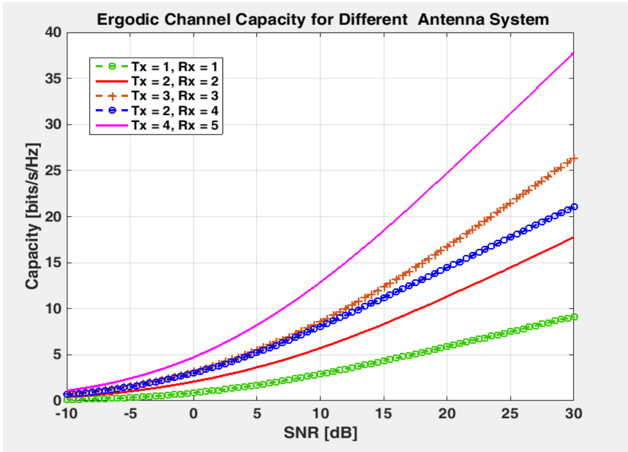
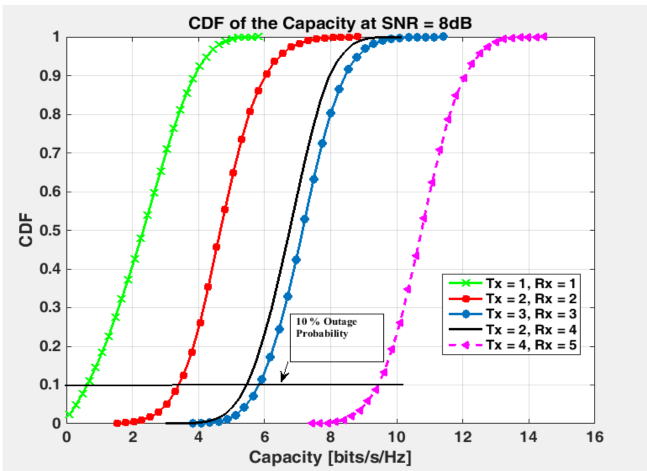


Table 4 Ergodic channel capacity of the MIMO $(M_T\times M_R)$ system

SNR (dB)	*Ergodic channel capacity (bits/s/Hz)*			
	2×2	*2×4*	*3×3*	*4×5*
10 dB	6	7.7	8.5	13
15 dB	8	11.2	12.5	18.7
20 dB	11	14.4	17	25
dB	14.5	17.6	22	32
30 dB	17.6	21	26.3	37.5

The probability of an outage at a constant SNR of 8 dB is depicted in Figure 9. The probability of achieving an average capacity for all combinations of MIMO antenna systems such as 1×1, 2×2, 2×4, 3×3 and 4×5 is about 50%.

Figure 9 CDF of the capacity at the SNR of 8 dB for $(M_T\times M_R)$ antenna configutions



It is observed that the average capacity for each configuration is almost equal, but the outage probability increases significantly with the increase in the number of antennas considering 10% outage probability. Probability of channel capacities exceeding 6, 8, 8.5 and 12 bits/s/Hz at a constant SNR of 8 dB is more than 90% for 2×2, 2×4, 3×3 and 4×5 antenna configurations. The MIMO ergodic channel capacity for the received diversity scheme on the AWGN channel is presented in Figure 10. For simulations, water filling algorithms and Singular-Value Decomposition (SVD) with M_T = 1 and M_R = 2, 3, 4, 5 antenna configurations have been used. The capacity performance for receiver diversity configurations using single transmitting antennas and multiple receiving antennas is shown in Table 5. From the Figure 11, it is observed that the average capacity for each configuration of receiver diversity scheme is almost similar, where as the outage probability increases significantly with the increase in the number of antennas considering 10% outage probability. Probability of channel capacities exceeding 4.7 to 5.7 bits/s/Hz at a constant SNR of 8 dB is more than 90% for M_T = 1 and M_R = 2, 3, 4, 5 antenna configurations.

Figure 10 Ergodic channel capacity for receive antenna diversity $(1\times M_R)$

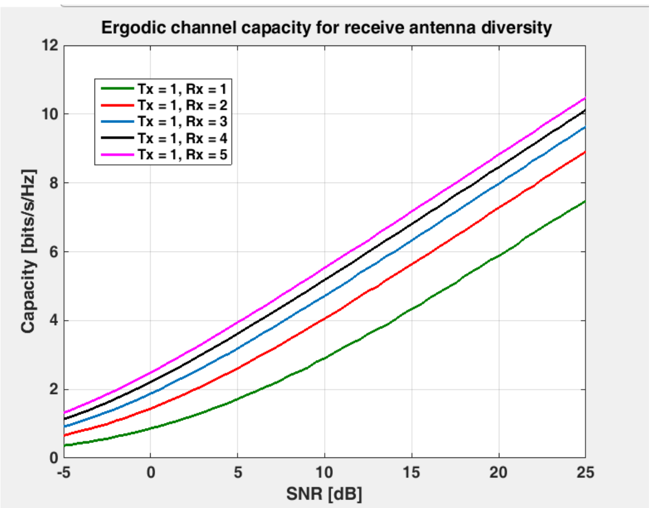
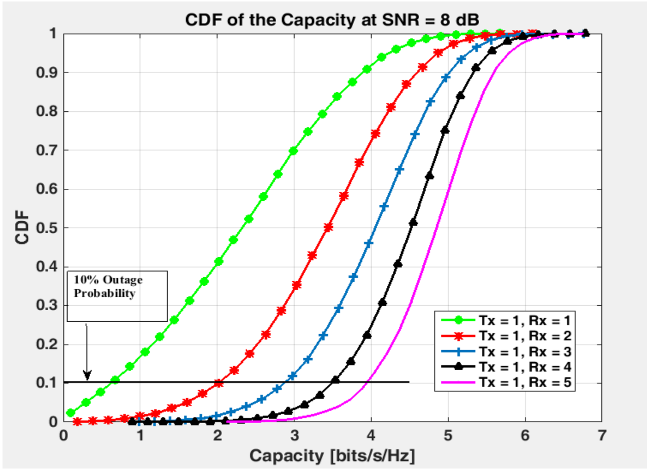


Table 5 Ergodic channel capacity of the MIMO $(1\times M_R)$ system

SNR (dB)	*Ergodic channel capacity (bits/s/Hz)*			
	1×2	1×3	1×4	1×5
10 dB	4	4.7	5.2	5.6
15 dB	5.7	6.2	6.8	7.2
20 dB	7.2	8	8.4	8.9
25 dB	8.9	9.7	10.1	10.5

Figure 11 CDF of the capacity at the SNR of 8 dB for $(1\times M_R)$ antenna configurations



7 Conclusion

For reliable communication, the MIMO technology has been proven to be robust against multipath fading effects in a wireless system. In this article, the wireless communication system using MRC $(1\times M_R)$ scheme has been proposed for diminishing the error rates. The system error rate performance has been analysed on Rayleigh fading channel using 1×2 and 1×4 antenna configuration. For the ergodic capacity and outage capacity performance the SVD method for channel matrix approximation and water filling algorithms have been employed for simulation. The ergodic capacity and outage capacity have been analysed for the MIMO system using multiple antennas $(M_T\times M_R)$ at both receiver and transmitter end as well as for the MIMO with receive diversity $(1\times M_R)$ scheme, where $M_T = M_R$. = 1 to 5 have been used. The simulation results in this arcle prove that at any constant SNR value, an increase in the number of antennas at both ends leads to a significant increase in outage capacity. The ergodic capacity at 10 dB SNR value using M_T = 2, 3, 4 and M_R = 2, 3, 4, 5 has been found to be in the range of 6 bit/s/Hz to 13 bits/s/Hz, which is better than the ergodic capacity analysed in the introduction section. Also using receive diversity scheme, the ergodic capacity has been found up to 5.5 bits/s/Hz at 10 dB SNR. The channel capacity increases linearly after 10 dB with an increase in SNR value further. The MRC scheme has proven to be the best method for improving BER presentation as well as significantly improving the channel capacity of the MIMO-OFDM system. From the simulation results of (1×4) antenna configuration under the MRC scheme, it is observed that even with a small increase of SNR, the BER improves rapidly in Rayleigh fading channels similar to AWGN channels. Considering this performance it is inferred that the

MRC scheme with (1 × 4) antenna configuration can be used for wireless communication if there is no space issue with the receiving device. Finally, after review and analysis of various schemes and simulation results, it is estimated that the proposed MRC scheme with (1 × 4) antenna configuration may be best suited for current and next-generation wireless systems.

Conflict of interest

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