Performance Analysis of MIMO-OFDM for 4G Wireless Systems under Rayleigh Fading Channel

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Abstract

MIMO-OFDM technology is a combination of multiple-input multiple-output (MIMO) wireless technology with orthogonal frequency division multiplexing (OFDM) that has been recognized as one of the most promising techniques to support high data rate and high performance in different channel conditions. Again, Alamouti's space time block coding scheme for MIMO system has drawn much attention in 4G wireless technologies just because of its decoding simplicity. This paper presents the performance evaluation of Alamouti's space-time block coded (ASTBC) MIMO-OFDM systems covering channel model, channel capacity, coding scheme and diversity gain. The mathematical model of capacity is derived for deterministic, random and correlated Rayleigh fading channels. The channel capacity per unit bandwidth is evaluated as a function of SNR. It is observed that the channel capacity increases with the number of antenna added to the system due to the more diversity gain of Alamouti's code. Finally we investigate the correlated MIMO fading channel with different correlation matrix. At the higher SNR value, independent and identically distributed (i.i.d) channel capacity outperforms the correlated channel capacity. But At very low SNR value correlated channel capacity outperforms the i.i.d channel capacity.

Keywords: *MIMO, OFDM, ASTBC, Channel Capacity*

1. Introduction

The key challenge of future wireless communication systems is to provide high data rate wireless access at high quality of service. Since spectrum is a scarce resource and propagation conditions are hostile due to fading caused by destructive addition of multi-path components and interference from other users, it is required to radically increase spectral efficiency and to improve link reliability as a solution. During the last decade, many researchers have proposed multiple-input multiple-output (MIMO) wireless technology that seems to meet these demands by offering increased spectral efficiency through spatial multiplexing gain and improved link reliability due to antenna diversity gain [1, 2]. In addition, the MIMO system containing multiple antennas both at transmitter and receiver end can potentially meet the growing demand for higher capacity in wireless communications [3, 4].The information capacity of wireless communication systems increases dramatically by using multiple transmitting and receiving antennas. Space-time coding, an effective approach for increasing data rate over wireless channels, employs coding techniques appropriate to multiple transmitting and receiving antennas. Hence, a new generalized complex orthogonal space time block code for several transmit antennas with full rate has been proposed in [5, 6]. In the fourth generation wireless communication systems the data rate may be as high as 1Gbps. For that, space-time coding techniques may be employed in conjunction with the multi-carrier code division multiple access (MC-CDMA) system to achieve very high data rate [7]. Different types of space-time trellis and block codes have been proposed for MC-CDMA systems in [8]. Many literatures has proposed space-time block coding schemes for orthogonal frequency division multiplexing (OFDM) systems based on the Alamuoti's scheme [9]. In frequency selective fading channels, space-time coded OFDM is a popular approach to provide transmit diversity and coding gains, which are termed as space-time trellis coded OFDM [10], and space-time block coded OFDM [11-16]. In particular, the combination of orthogonal space time block codes (OSTBCs) and OFDM, or simply OSTBC-OFDM has drawn much attention because it attains the maximum transmit diversity and has a simple maximum-likelihood (ML) receiver structure [12-16]. OFDM in conjunction with MIMO techniques allows us to realize and satisfy the ever growing demands of multimedia services and applications. OFDM has already been used successfully in standards for digital audio broadcasting (DAB), terrestrial video broadcasting (DVB-T), and wireless local area networks (WLANs) [17]. In this paper, we present an Alamouti's STBC coded MIMO-OFDM system for various antenna configurations to fulfill the demand of 4G wireless technology. A brief discussion on Alamouti's STBC is presented. Simulation results of Alamouti's STBC with various antenna configurations are analyzed to evaluate the performance in terms of BER. Finally, mathematical models of MIMO channel capacity for deterministic, random fading ergodic and correlated MIMO channels are presented and capacity of the different MIMO channels is evaluated for various antenna configurations under different channel correlation matrix.

2. Background

In this review section, we first describe space time block coded MIMO-OFDM system model. Then, we briefly explain some most attractive features of MIMO-OFDM wireless communication.

2.1 ASTBC-OFDM System Model

Consider a space time block coded MIMO-OFDM system [18] equipped with N_T transmit antennas and N_R receive antennas as illustrated in Figure 1. The message bit sequence is mapped into a sequence of BPSK symbols which will be converted into N parallel symbol streams after serial-to-parallel (STP) conversion. Each of the N parallel symbol streams is then encoded by the space-time block code (STBC) encoder into $\left\{X_i^{(t)}\right\}_{i=1}^{N_T}$ $i = 1,2,3,\cdots\cdots,N_T$ where i is the antenna index and t is the symbol time index. The number of symbols in a space-time codeword is $N = N_T \times T$. Then the symbol streams are subjected to inverse fast Fourier transform (IFFT) operation followed by cyclic prefix insertion between two consecutive OFDM symbols in order to reduce the effect of the delay spread of the multipath channels. The length of the CP is adjustable and must be set in order to keep a bandwidth efficient system without occurring inter symbol interference or inter carrier interference. At the receiver, after removing the CP, and applying FFT, the transmitted symbol stream $\left\{\tilde{X}_i^{(t)}\right\}_{i=1}^{N_T}$ is estimated using the received signal $\left\{\tilde{Y}_j^{(t)}\right\}_{j=1}^{N_R}$. Assume the channel gain matrix h_{ji}^t follows the Rayleigh distribution from the i^{th} transmit antenna to the j^{th} receive antenna over the t^{th} symbol period. If the channel gains do not change during T symbol periods, the symbol time index can be omitted and as long as the transmit antennas and receive antennas are spaced sufficiently apart, $N_T \times N_R$ fading gains $\{h_{ij}\}$ can be assumed to be statistically independent. If X_i^T is the transmitted signal from the i^{th} transmit antenna during t^{th} symbol period, the received signal at the j^{th} receive antenna during t^{th} symbol period is given by equation (1), where z_j^t is the noise process at the j^{th} receive antenna during t^{th} symbol period, which is modeled as the zero mean circular symmetric complex Gaussian (ZMCSCG) noise of unit variance, and is the average energy of each transmitted signal. In general we can write in equation (2)

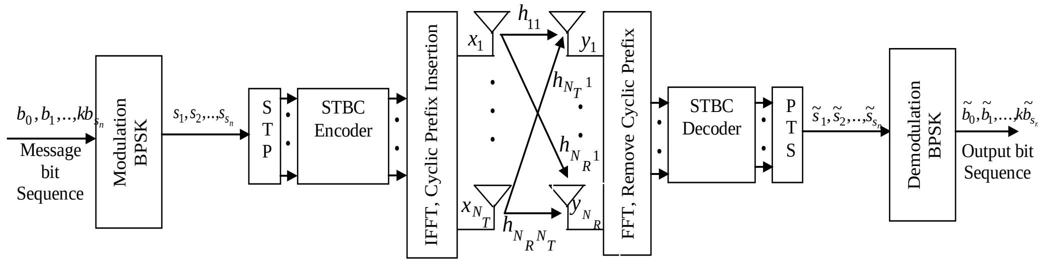

Figure 1. Block Dagram of Space Time Block Coded MIMO-OFDM system Structure

$$y_j^t = \sqrt{\frac{E_x}{N_T N_0}} \begin{bmatrix} h_{j1}^t & h_{j2}^t & h_{j3}^t \cdots h_{jN_T}^t \end{bmatrix} \begin{bmatrix} X_1^t \\ X_2^t \\ X_3^t \\ \vdots \\ X_{N_T}^T \end{bmatrix} + z_j^t \tag{1}$$

$$Y = \sqrt{\frac{E_x}{N_T N_0}} HX + Z \tag{2}$$

2.2 Some Features of MIMO-OFDM

Spatial multiplexing gain: the transmission of multiple data streams over more than one antenna is called spatial multiplexing [19]. The advantage of spatial multiplexing is linear capacity gains in relation to the number of transmit antennas. This gain, referred to as spatial multiplexing gain, is realized by transmitting independent data signals from the individual antennas.

Spatial diversity gain: spatial diversity improves the signal quality and achieves a higher signal to noise ratio at the receiver side. Signal power in a wireless channel fluctuates randomly or fades. Diversity is a powerful technique to mitigate fading in wireless links. Among many different types of antenna diversity techniques, transmit diversity techniques have been widely adopted in practice since it is useful in reducing the processing complexity of the receiver and it requires multiple antennas only on the transmitter side.

3. MIMO Channel Model

In wireless communications, reflection, diffraction, scattering and shadowing of the transmitted signals due to surrounding objects causes multipath propagation and as a consequence the transmitted signals arrive at the receiver with different phase angles, different amplitude and at different time intervals. The amplitude fluctuation of the received signal is called signal fading and we assume the fading process follows a Rayleigh probability distribution function. In time domain, the channel response from the i^{th} transmit antenna to the j^{th} receive antenna can be given as

$$h_{i,j}(t) = \sum_{l=0}^{L-1} \alpha_{i,j}(l)\delta(t-\tau_l) \tag{3}$$

where $\alpha_{i,j}(l)$ is the multi-path gain coefficient, L denotes the number of resolvable paths, and τ_l represents the path delay time of l^{th} multi-path component. The frequency response of the channel is given by

$$h^k{}_{i,j}(f) = \sum_{l=0}^{L-1} \alpha^k{}_{i,j}(l) e^{-j2\pi f \tau_l} \tag{4}$$

4. Space Time Block Code

A complex orthogonal space-time block code for two transmit antennas was developed by Alamouti [20]. In the Alamouti encoder, two consecutive symbols x_1 and x_2 are encoded with the following space-time codeword matrix as follows:

$$X = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}$$

Alamouti encoded signal is transmitted from the two transmit antennas over two symbol periods. During the first symbol period at $t = T$, two symbols x_1 and x_2 are simultaneously transmitted from the two transmit antennas. During the second symbol period $t = 2T$, these symbols are transmitted again, where $-x_2^*$ is transmitted from the first transmit antenna and x_1^* transmitted from the second transmit antenna. For Maximum Likelihood signal detection of Alamouti's space-time coding scheme, we assume that two channels gains $h_1(t)$ and $h_2(t)$ remain constant over two consecutive symbol periods such that

$$h_1(t) = h_1(t+T) = h_1 = |h_1| e^{j\theta 1}$$
$$h_2(t) = h_2(t+T) = h_2 = |h_2| e^{j\theta 2}$$

Where $|h_1|$ and $e^{j\theta 1}$ denote the amplitude gain and phase rotation over the two symbol periods. At the receiver the received signals y_1 and y_2 at time t and $t+T_s$ can be given as

$$y_1 = h_1 x_1 + h_2 x_2 + z_1$$

$$y_2 = h_1 x_2^* + h_2 x_1^* + z_2$$

where z_1 and z_2 are the additive noise at time t and $t + T_s$ respectively. In this paper we have proposed Alamouti's space time block code for two transmit antenna and more than one receive antenna case.

5. Channel Capacity of MIMO-OFDM System

Compared to a conventional single antenna system, the channel capacity of a multiple antenna system with N_T transmit and N_R receive antennas can be increased by the factor of $\min(N_R, N_T)$ without using additional transmit power or spectral bandwidth. Due to the ever increasing demand of faster data transmission speed in the recent or future telecommunication systems, the multiple antenna systems have been actively investigated [21]. In this section, we derive the expression of deterministic MIMO channel where the channel state information (CSI) is perfectly known to both receiver and the transmitter side and hence channel capacity for deterministic MIMO channel where the CSI is perfectly known to receiver but unknown to the transmitter side is presented. Then we derive channel capacity for the random channel i.e. ergodic channel where the channel matrix $\mathbf{H}$ is probabilistic and it is usually assumed that $\mathbf{H}$ represents Rayleigh fading. Every time the channel transmits, a new realization of $\mathbf{H}$ is drawn. In this situation new thoughts in coding and throughput must be considered [22]. We model the MIMO correlated fading channel involving correlation between transmit and receive antennas, transmit antennas only and receive antennas only as in [23] because the MIMO channel capacity largely depends on the correlation between antennas.

5.1 Deterministic Channel Capacity of MIMO-OFDM System

For a MIMO system with N_T transmit and N_R receive antennas as shown in Figure 1, a narrowband time-invariant wireless channel can be represented by $N_R \times N_T$ deterministic matrix $\mathbf{H} \in C^{N_R \times N_T}$. Consider a transmitted symbol vector $\mathbf{x} \in C^{N_T \times 1}$ which is composed of N_T independent input symbols $x_1, x_2, x_3, \ldots\ldots, x_{N_T}$. Then, the received signal $\mathbf{y} \in C^{N_R \times 1}$ can be written in a matrix form as follows:

$$\mathbf{y} = \sqrt{\frac{\mathbf{E}_x}{N_T}}\mathbf{H}\mathbf{x} + \mathbf{z} \tag{5}$$

where $\mathbf{z} = \left(z_1, z_2, \ldots\ldots, z_{N_R}\right)^T \in C^{N_R \times 1}$ is a noise vector which is assumed to be zero mean circular symmetric complex Gaussian (ZMCSCG). The autocorrelation of transmitted signal vector is defined as

$$\mathbf{R}_{xx} = E\left\{\mathbf{x}\mathbf{x}^H\right\} \tag{6}$$

The capacity of a deterministic channel is defined as $C = \max_{f(x)} I(\mathbf{x}; \mathbf{y})$ bits/channel use in which $f(\mathbf{x})$ is the probability density function (PDF) of the transmit signal vector $\mathbf{x}$, and $I(\mathbf{x};\mathbf{y})$ is the mutual information of random vectors $\mathbf{x}$ and $\mathbf{y}$. From the fundamental principle of the information theory, the mutual information of the two continuous random vectors $\mathbf{x}$ and $\mathbf{y}$ is given as

$$I(x;y) = H(y) - H(y|x) \tag{7}$$

in which $H(y)$ is the differential entropy of $\mathbf{y}$ and $H(y|x)$ is the conditional differential entropy of $\mathbf{y}$ when $\mathbf{x}$ is given. Using the statistical independence of the two random vectors $\mathbf{z}$ and $\mathbf{x}$ in Equation (5), we can write equation (7) as follows

$$I(x;y) = H(y) - H(z) \tag{8}$$

From the equation (8) we observe that $H(z)$ is a constant, we can see that the mutual information is maximized when $H(y)$ is maximized. Now, the auto-correlation matrix of y is given as

$$\mathbf{R}_{yy} = E\{\mathbf{y}\mathbf{y}^H\} \tag{9}$$

Putting the value of equation (5) in equation (9) we find

$$\mathbf{R}_{yy} = \frac{\mathbf{E}_x}{N_T}\mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H + \mathbf{N}_0\mathbf{I}_{N_R} \tag{10}$$

where $\mathbf{E}_x$ the energy of the transmitted signals and $\mathbf{N}_0$ is the power spectral density of the additive noise $\{z_i\}_{i=1}^{N_R}$. The differential entropy $H(\mathbf{y})$ is maximized when y is ZMCSCG which consequently requires $\mathbf{x}$ to be ZMCSCG. The mutual information can be found from equation (8) as follows

$$I(\mathbf{x};\mathbf{y}) = \log_2 \det(\mathbf{I}_{N_R} + \frac{\mathbf{E}_x}{N_T\mathbf{N}_0}\mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H) \text{ bps/Hz} \tag{11}$$

Then, the channel capacity of deterministic MIMO channel in the case of CSI known to both receiver and transmitter side is expressed as

$$C = \max_{Tr(\mathbf{R}_{xx}=N_T)} \log_2 \det(\mathbf{I}_{N_R} + \frac{\mathbf{E}_x}{N_T\mathbf{N}_0}\mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H) \text{ bps/Hz} \tag{12}$$

When $\mathbf{H}$ is not known at the transmitter side, one can spread the energy equally among all the transmit antennas so that the autocorrelation function of the transmit signal vector $\mathbf{x}$ is given as

$$\mathbf{R}_{xx} = \mathbf{I}_{N_T}$$

Finally the channel capacity is given as

$$C = \log_2 \det(\mathbf{I}_{N_R} + \frac{\mathbf{E}_x}{N_T\mathbf{N}_0}\mathbf{H}\mathbf{H}^H) \text{ bps/Hz} \tag{13}$$

$$C = \sum_{i=1}^{r} \log_2(1 + \frac{\mathbf{E}_x}{N_T\mathbf{N}_0}\lambda_i) \tag{14}$$

where $r = \min(N_T, N_R)$ denotes the rank of $\mathbf{H}$ and λ_i denotes the i^{th} eigen value.

5.2 Ergodic Channel Capacity of MIMO-OFDM System

In above section, we have assumed that MIMO channels are deterministic where the channel gain remains constant. But in general case, MIMO channels change randomly and hence $\mathbf{H}$ is a random matrix which means that its channel capacity is also randomly time varying and follows an ergodic process in practice. Then, we consider the following statistical notion of the MIMO channel capacity:

$$\overline{C} = E\{(\max_{Tr(\mathbf{R}_{xx}=N_T)} \log_2 \det(\mathbf{I}_{N_R} + \frac{\mathbf{E}_x}{N_T \mathbf{N}_0} \mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H)\} \text{ bps/Hz}$$

which is frequently known as an ergodic channel capacity. The ergodic channel capacity for the open-loop system without using CSI at the transmitter side from Equation (10) is given as

$$\overline{C}_{OL} = E\{\sum_{i=1}^{r} \log_2 (1 + \frac{\mathbf{E}_x}{N_T \mathbf{N}_0} \lambda_i)\} \tag{15}$$

Similarly, the ergodic channel capacity for the closed loop (CL) system using CSI at the transmitter side is given as

$$\overline{C}_{CL} = E\{\sum_{i=1}^{r} \log_2 (1 + \frac{\mathbf{E}_x}{N_T \mathbf{N}_0} \gamma_i^{opt} \lambda_i)\} \tag{16}$$

Sometimes the ergodic channel capacity is expressed as a function of the outage channel capacity. The outage probability can be defined as

$$P_{out}(R) = \Pr(C(\mathbf{H}) < R) \tag{17}$$

5.3 Capacity of MIMO Correlated Fading Channel

In general, the MIMO channel gains are not independent and identically distributed (i.i.d.) and the capacity of the MIMO channel are closely related to the channel correlation. For this reason, we consider the capacity of the MIMO channel when the channel gains between transmit and received antennas are correlated. We model the correlated channel as follows:

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2} \tag{18}$$

where $\mathbf{H}_w$ denotes the independent and identically distributed (i.i.d) Rayleigh fading channel gain matrix and $\mathbf{R}_t$ is the correlation matrix taking correlations between the transmit antennas , $\mathbf{R}_r$ is the correlation matrix taking correlations between the receive antennas. Then the correlated channel capacity can be represented as

$$C = \log_2 \det(\mathbf{I}_{N_R} + \frac{\mathbf{E}_x}{N_T \mathbf{N}_0} \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t \mathbf{H}_w^H \mathbf{R}_r^{H/2}) \tag{19}$$

From the equation (19), we consider four cases for simulation. The correlation matrix can be given as in [24, 25].

Case 1: Correlation exists between transmit and receive antennas, transmit antennas and receive antennas but the correlation matrix $\mathbf{R}_t$ and $\mathbf{R}_r$ are identical.

$$\mathbf{R_t} = \begin{bmatrix} 1 & 0.76e^{j0.17\pi} & 0.43e^{j0.35\pi} & 0.25e^{j0.53} \\ 0.76e^{j0.17\pi} & 1 & 0.76e^{j0.17\pi} & 0.43e^{j0.35\pi} \\ 0.43e^{j0.35\pi} & 0.76e^{j0.17\pi} & 1 & 0.76e^{j0.17\pi} \\ 0.25e^{j0.53} & 0.43e^{j0.35\pi} & 0.76e^{j0.17\pi} & 1 \end{bmatrix}$$

$$\mathbf{R_r} = \begin{bmatrix} 1 & 0.76e^{j0.17\pi} & 0.43e^{j0.35\pi} & 0.25e^{j0.53} \\ 0.76e^{j0.17\pi} & 1 & 0.76e^{j0.17\pi} & 0.43e^{j0.35\pi} \\ 0.43e^{j0.35\pi} & 0.76e^{j0.17\pi} & 1 & 0.76e^{j0.17\pi} \\ 0.25e^{j0.53} & 0.43e^{j0.35\pi} & 0.76e^{j0.17\pi} & 1 \end{bmatrix}$$

Case 2: Correlation exists between transmit and receive antennas, transmit antennas and receive antennas but the correlation matrix $\mathbf{R}_t$ and $\mathbf{R}_r$ are not identical.

6. Simulation Results

Simulation results are presented to evaluate the performance of ASTBC coded MIMO-OFDM system with more than one antenna at the receiver and channel capacity for MIMO-OFDM system under independent, identically distributed (i.i.d) and spatially correlated MIMO-OFDM Rayleigh fading channels. This section is divided into two parts, i.e. the performance analysis of ASTBC coded MIMO-OFDM system and capacity analysis of deterministic, ergodic and spatially correlated MIMO-OFDM system under Rayleigh fading channel with different correlation matrix.

6.1 Performance Analysis of ASTBC MIMO-OFDM System

At first the performance of Alamouti's Space Time Block Coded MIMO-OFDM system under Rayleigh fading channel is investigated with various antennas configurations. The

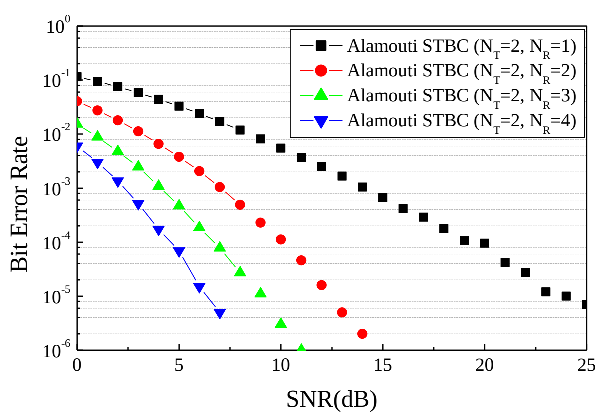

Figure 2. BER Performance of Alamouti's STBC for Various Antenna Configuration

simulation model employs BPSK modulation scheme and Alamouti's coding scheme using two transmit antennas and more than one receive antennas. In this case, we assume that transmit and receive antennas are uncorrelated, that is, those antennas are separated far enough from each other so that the fading processes affecting those antennas can be considered to be independent and identically distributed. We also assume that the channel coefficients are constant during each OFDM frame. Figure 2 compares the BER for different number of receive antennas and two transmit antennas system under Rayleigh fading channel. We observe that the performance of two transmit antennas with four receive antennas is much better than that of the system with two transmit antenna and less than four receive antennas in term of BER. We observe that the receive diversity gain increases with the number of receive antenna in the system and consequently the BER reduces quickly at the low value of SNR that improves the system performance of ASTBC MIMO-OFDM in terms of diversity gain.

6.2 Performance Analysis of MIMO Channel System

The performance of deterministic, ergodic and correlated MIMO channel capacity per unit bandwidth is investigated as a function of SNR. We also investigated the cumulative density function in the case of ergodic channel capacity. Finally the channel capacity of correlated MIMO channel for case 1 and case 2 as described above in section 5.3 is investigated. Figure 3 and Figure 4 shows both deterministic channel capacity and MIMO ergodic channel

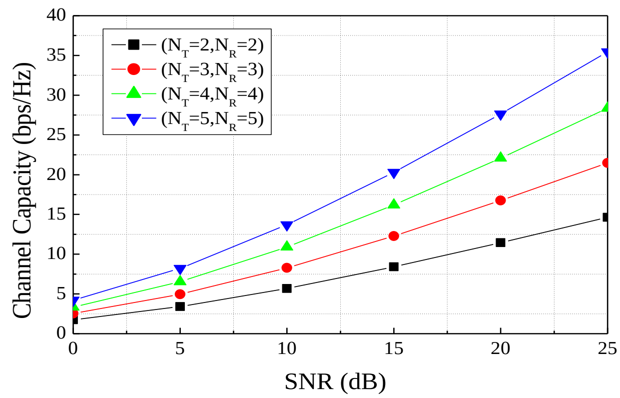

Figure 3. Deterministic MIMO Channel Capacity in Terms of SNR

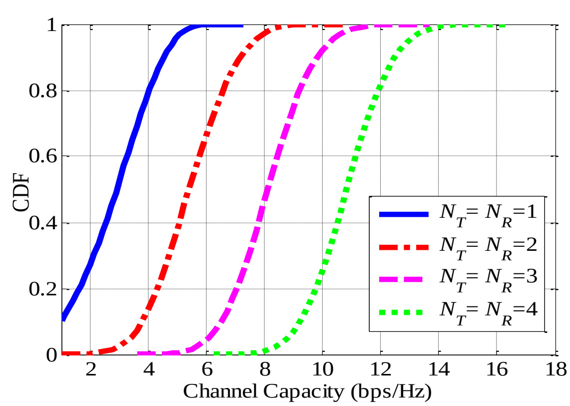

Figure 4. Ergodic MIMO Channel Capacity in Terms of SNR

capacity system increases with increasing the number of transmit and receive antennas in the system under consideration. Figure 5 shows the capacity of i.i.d and correlated channel in terms of SNR with correlation exists between the transmit antennas and receive antennas but same correlation matrix. At 15 dB of SNR value 4×4 i.i.d channel provide 16.22 bps/Hz whereas 3×3 i.i.d channel provides 11.8 bps/Hz and 4×4 correlated channel provides12.34 bps/Hz. Figure 6 shows the capacity of i.i.d and correlated channel in terms of SNR with correlation exists between the transmit antennas and receive antennas but different correlation matrix. In this case we notice that 4×4 i.i.d channel provide 22 bps/Hz whereas 4×4 correlated channel provides 14 bps/Hz. So i.i.d channel outperforms the correlated channel.

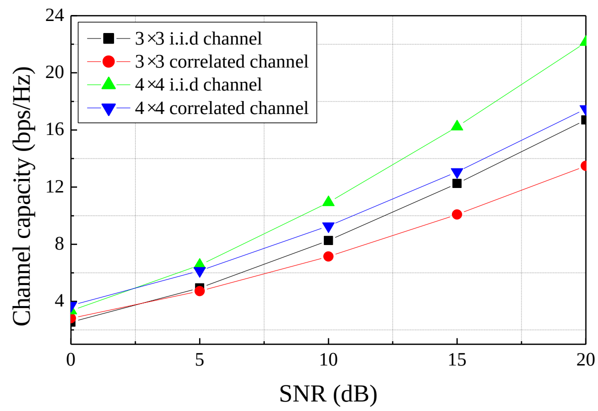

Figure 5. Capacity of i.i.d and Correlated Channel in Terms of SNR with Correlation Exists between the Transmit Antennas and Receive Antennas but Same Correlation Matrix

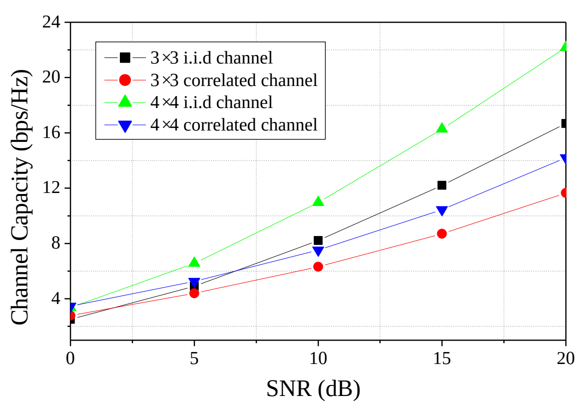

Figure 6. Capacity of i.i.d and Correlated Channel in terms of SNR with Correlation Exists between the Transmit Antennas and Receive Antennas but Different Correlation Matrix

7. Conclusion

In this paper we evaluated the performance of the ASTBC MIMO-OFDM system under Rayleigh fading channel. We observe that the performance of two transmit antennas with more receive antennas is much better than that of the system with two transmit antenna and less receive antennas in term of BER due to the more diversity gain of Alamouti's code. We also derived the mathematical model of deterministic, ergodic and correlated Rayleigh fading channel capacity where the CSI is perfectly known to the receiver and unknown to the transmitter side. We investigated the MIMO channel capacity with the various number of receive and transmit antennas. We observe that the channel capacity increases with the number of antenna added to the system. Finally we investigated the correlated MIMO fading channel with different correlation matrix. At the higher SNR value, i.i.d channel capacity outperforms the correlated channel capacity. But At very low SNR value correlated channel capacity outperforms the i.i.d channel capacity. It can be seen that MIMO-OFDM system can significantly increase the channel capacity of the system with the inclusion of more antenna to the system.

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