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Capacity and performance analysis of space-time block coded MIMO-OFDM systems over Rician fading channel

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***Abstract*—This paper presents an analysis on the capacity and performance of MIMO-OFDM systems. The work is focused on the capacity of MIMO-OFDM systems over rician fading channel, in the case of the channel being known at the receiver only, which is more practical case of the channel. Simple expression for capacity is derived for the case of correlated rician fading. The performance of some MIMO-OFDM implementations with rician fading model is presented using an Alamouti coding scheme and Simulation results are obtained for both capacity and performance analysis.

***Keywords*—MIMO, OFDM, rician distribution, space time block codes (STBC).

I. INTRODUCTION

MIMO (Multiple Input, Multiple Output) uses multiple antennas to transmit and receive multiple wireless signals at the same time, causing better wireless system performance to improve all three parameters i.e. speed, range and reliability compare to other conventional systems. The algorithms used most commonly in MIMO are Singular Value Decomposition (SVD), Water filling and Space-Time Block Coding. When the Channel State Information (CSI) is perfectly known at the receiver and transmitter, SVD is used to convert the channel into a set of parallel subchannels, usually called Singular Value (SV) channels. Water filling improves the system performance by allocating more power to those SV channels that have better quality. However, it is not practical to assume the CSI is perfectly known at the transmitter side. STBC only requires CSI at the receiver side [1]. It is well known that the performance degradation take place due to multi-path fading channels. Different equalization techniques are used to combat effect of Inter Symbol Interference (ISI), but this can be done at the cost of complexity. An alternative to these equalizers is OFDM [2]. Orthogonal frequency division multiplexing (OFDM), is a modulation technique to carry a data on different frequency channels. OFDM can provide simplicity on both side i.e. transmitter and receiver, and also improve the spectral efficiency of wireless system [3]. Existing research is mainly focused on obtaining the capacity and performance analysis curves for various MIMO configurations, assuming Rayleigh fading and independent and identically distributed MIMO-OFDM sub-channel. So far, the capacity of MIMO-OFDM systems in the case of the channel being known at the transmitter and receiver (leading to a water-filling solution) [4] and in the more practical case of the channel known at the receiver only has been developed for Rayleigh fading channel. Now we have to think for the capacity and performance analysis of MIMO-OFDM system in Rician fading channel considering STBC.

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II. SYSTEM MODEL

The general system model that consists M_T transmit and M_R receive antennas is shown in Figure 1. Each channel is modeled as a Finite Impulse Response (FIR) filter with L taps. For $L = 1$ the channel is flat fading, whereas for $L > 1$ the channel is frequency selective. $h_{i,j}(\tau, t)$ is the time-varying channel response between j-th ($j = 1, 2, ..., M_T$) transmit antenna and the i-th ($i = 1, 2, ..., M_R$) receive antenna while each antenna transmits N sub-carrier signals. In total there are $M_T \times N$ subchannels.

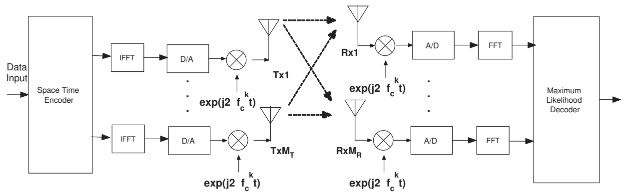

Fig. 1. MIMO-OFDM System Model

A. Transmitter description

At the transmitter, the information sequence $x = [x_0, x_1, ..., x_{N-1}]$ is encoded by a space time block code (STBC) to produce the N sequences $s_k = \left[s_k^{(0)}, s_k^{(1)}, ..., s_k^{(N-1)}\right]^T$, where $s_k^{(i)}$is the coded symbol transmitted from the i-th antenna to the k-th OFDM subchannel.Transmission matrix for two transmit antenna using Alamouti code [5] is given as

$$\mathcal{G} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix} \tag{1}$$

where the rows denote time instances and columns denote transmit antennas. Thus, at time $t = 1$, s_1 and s_2 will be transmitted from antennas 1 and 2 respectively, and at time $t = 2$, $-s_2^*$ and s_1^* will be transmitted from antennas 1 and 2 respectively. Consider an OFDM-based multiplexing system with M_T transmitting and M_R receiving antennas. The transmitter is formed by M_T similar branches, each branch consisting of an OFDM modulator followed by digital to analog converter. The OFDM transceiver is shown in the Figure. 2, where $s_k^{(i)}$ is the OFDM block to be transmitted on the i-th transmit antenna. $s_k^{(i)}$ is then processed by an inverse DFT matrix. AT the output of the IDFT, a guard interval of D samples is inserted at the beginning of each block. It consists of a cyclic extension of the time domain OFDM symbol of size larger than the channel impulse response, known as cyclic prefix. Cyclic prefix (CP) is between each block in order to transform the multi-path linear convolution into circular one. After parallel to serial (P/S) transformation and digital to analog conversion (DAC), the signal is sent through a frequency-selective channel. The transmitted data symbols in frequency vectors are given as

$$\mathbf{c}_k == \left[c_k^{(0)} c_k^{(1)} ... c_k^{(M_T-1)} \right]^T \tag{2}$$

where $c_k^{(i)}$ denote the data symbol transmitted from the ith antenna on the kth tone. $k = 0, 1, ..., N-1$, N is number of OFDM subcarriers.

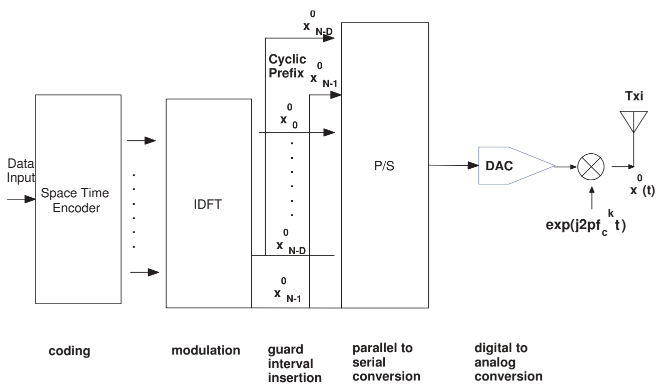

Fig. 2. Transmitter architecture

B. Channel model

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 channel response in frequency domain $\mathbf{H}\left(e^{j2\pi\theta}\right)$ for each subcarrier consists of L channel-matrix taps of size $M_R \times M_T$ is given by

$$\begin{pmatrix} h_{0,0}(l) & h_{0,1}(l) \ldots h_{0,M_T-1}(l) \\ h_{1,0}(l) & h_{1,1}(l) \ldots h_{1,M_T-1}(l) \\ \vdots & \vdots \ddots \vdots \\ h_{M_R-1,0}(l) & h_{M_R-1,1}(l) \ldots h_{M_R-1,M_T-1}(l) \end{pmatrix} e^{-j2\pi l\theta}$$

Where $0 \leq \theta < 1$ and $h_{i,j}(l)$ is the l-th tap of the impulse response. which is assumed constant during one frame interval and changes independently in subsequent frames (quasi-static assumption).

The $M_R \times 1$ discrete-time received signal vector $y[n]$ can be writen as [6]:

$$y[n] = \sum_{l=0}^{L-1} H_l x[n-l] \tag{4}$$

where x[n] is discrete-time $M_T \times 1$ transmitted signal vector.While H_l is l^{th} tap of $M_R \times M_T$ complex-valued random channel impulse response matrix. It is assumed that the elements of the individual H_l are correlated but different scatterer clusters are uncorrelated, i.e.,

$$\mathbf{E}\left[vec\{\mathbf{H}_l\}vec^H\{\mathbf{H}_{l'}\}\right] = \mathbf{0}_{M_R M_T} \text{ for } l \neq l' \tag{5}$$

where $vec\{\mathbf{H}_l\} = \left[\mathbf{h}_{l,0}^T \mathbf{h}_{l,1}^T ... \mathbf{h}_{l,M_T-1}^T\right]$, $\mathbf{0}_{M_R M_T}$ is $M_R M_T \times M_R M_T$ zero matrix, while $\mathbf{h}_{l,k}$ is the k^{th} column of the matrix $\mathbf{H}_l$ and represented as $\mathbf{h}_{l,k} = \left[h_{l,k}^0 h_{l,k}^1 ... h_{l,k}^{N_R-1}\right]^T$.
Here the Additive White Gaussian Noise (AWGN) channel with Ricean fast fading is assumed, so there are L LOS components and elements of $\mathbf{h}_{l,k}$ are distributed as $\mathcal{N}_c\left(\frac{\mu_l}{\sqrt{2}}(1+j), 2\sigma_l^2\right)$, where $\mathcal{N}_c$ is circularly symmetric complex Gaussian distribution. The real and imaginary parts of $\mathbf{H}_l$ each is distributed as $\mathcal{N}\left(\frac{\mu_l}{\sqrt{2}}, \sigma_l^2\right)$ and the distribution of the magnitudes of the elements of $\mathbf{H}_l$ have the following Ricean probability density function (pdf).

$$f_R(r) = 2(1+K)re^{-(1+K)r^2-K} I_0(2\sqrt{K(1+K)r}) \tag{6}$$

where I_0 is the zeroth order modified Bessel function. As $\mathbf{H}_l$ is Ricean distribution can be written as:

$$\mathbf{H}_l = \bar{\mathbf{H}}_l + \widetilde{\mathbf{H}}_l, \text{ for } l = 0, 1, ..., L-1 \tag{7}$$

Here $\mathbf{H}_l$ is decomposed into the sum of a fixed component $\bar{\mathbf{H}}_l$, which is LOS (Ricean) component and a variable component $\widetilde{\mathbf{H}}_l$ [7].

$$\bar{\mathbf{H}}_l = \frac{\mu_l}{\sqrt{2}}(1+j) I_{M_R \times M_T} \text{ for } l = 0, 1, ..., L-1 \tag{8}$$

where $\mu_l^2 = \frac{K}{K+1}$ and $\sigma_l^2 = \frac{1}{K+1}$, here K is rice factor. And $I_{M_R \times M_T}$ is the identity matrix of order $M_R \times M_T$. In case of pure Rayleigh fading $\bar{\mathbf{H}}_l = \mathbf{0}_{M_R M_T}$, whereas for Rician fading $\bar{\mathbf{H}}_l \neq \mathbf{0}_{M_R M_T}$.

$$\widetilde{\mathbf{H}}_l = \mathbf{R}_l^{1/2} \mathbf{H}_{w,l} \text{ for } l = 0, 1, ..., L-1 \tag{9}$$

The elements of $\widetilde{\mathbf{H}}_l$ are circularly symmetric complex Gaussian random variables[1] and $\mathbf{R}_l$ is covariance matrices of

[1] A circularly symmetric complex Gaussian random variable is a random variable $z = (x+jy) \sim C\mathcal{N}(0, \sigma^2)$, where x and y are independent and identically distributed (i.i.d.) $\mathcal{N}(0, \sigma^2/2)$.

$\mathbf{H}_l$. Whereas the elements of an uncorrelated $M_R \times M_T$ matrix $\mathbf{H}_{w,l}$ are i.i.d. complex random variables with zero mean and unit variance. It is assumed in [6] that the fading correlations are the same for all transmit antennas.

$$[\mathbf{R}_l]_{m,n} = 2\sigma_l^2 \rho_l \left((n-m)\Delta, \bar{\theta}_l, \delta_l\right) \text{ for } l = 0, 1, ..., L-1 \quad (10)$$

where, $\rho_l\left(s\Delta, \bar{\theta}_l, \delta_l\right) = \mathbf{E}\left\{h_{l,k}^r \left(h_{l,k}^{r+s}\right)^*\right\}$ is a fading correlation between receiver antenna elements [8]. Also ρ_l is a function of the antenna spacing Δ, mean angle of arrival $\bar{\theta}_l$ and the angular spread δ_l. For a small angular spread the correlation can be written as [8]:

$$\rho_l\left(s\Delta, \bar{\theta}_l, \delta_l\right) = e^{-j2\pi s\Delta cos(\bar{\theta}_l)} e^{-0.5(2\pi s\Delta sin(\bar{\theta}_l)\sigma_{\theta,l})^2} \quad (11)$$

C. Receiver discription

The block diagram of receiver is shown in Figure. 3.

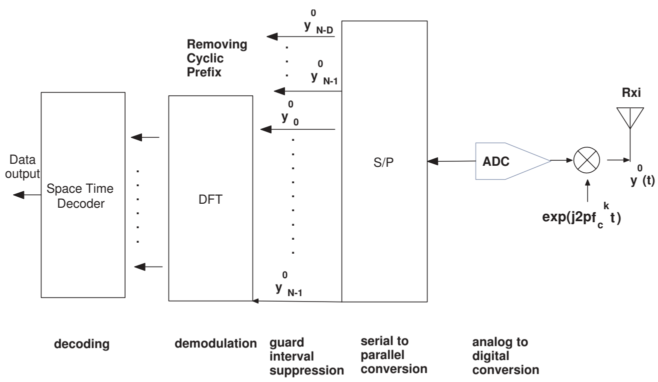

Fig. 3. Receiver architecture

The received signal is converted from analog to digital (ADC) followed by serial to parallel (S/P) transformation. Both guard interval and cyclic prefix are then suppressed. The signal is processed by discrete Fourier transform (DFT).

The reconstructed data vector for the kth tone can be written as

$$\mathbf{r}_k = \sqrt{E_s}\mathbf{H}\left(e^{j2\pi(k/N)}\right)\mathbf{c}_k + \mathbf{n}_k, \text{ for } k = 0, 1, ..., N-1 \quad (12)$$

where $\mathbf{H}\left(e^{j2\pi(k/N)}\right) = \sum_{l=0}^{L-1} \mathbf{H}_l e^{j2\pi l(k/N)}$ for $0 \leq \theta < 1$, while the constant E_s is an energy normalization factor and $\mathbf{n}_k$ is the white additive Gaussian noise satisfying

$$\mathbf{E}\left\{\mathbf{n}_k \mathbf{n}_l^H\right\} = \sigma_n^2 \mathbf{I}_{M_R} \quad (13)$$

where $\mathbf{I}_{M_R}$ is $M_R \times M_R$ identity matrix.

The maximum-likehood (ML) decoder computes the vector sequence $\hat{\mathbf{c}}_k$ $(k = 0, 1, ..., N-1)$, given as

$$\hat{\mathbf{C}} = \arg\min_C \sum_{k=0}^{N-1} \|\mathbf{r}_k - \mathbf{H}(e^{j\frac{2\pi}{N}k})\mathbf{c}_k\|^2$$

where $\hat{\mathbf{C}} = [\hat{\mathbf{c}}_0 \hat{\mathbf{c}}_1 ... \hat{\mathbf{c}}_{N-1}]$

III. Capacity of MIMO-OFDM System Under Rician Fading

A. Mutual information

In this section the mutual information of an OFDM-based system is derived with CSI available at the receiver using the model discussed in section II. The received vector can be written as

$$\mathbf{r} = \mathbf{Hc} + \mathbf{n} \quad (14)$$

where $\mathbf{r} = \left[\hat{\mathbf{c}}_0^T \hat{\mathbf{c}}_1^T \ldots \hat{\mathbf{c}}_{N-1}^T\right]^T$, $\mathbf{c} = \left[\mathbf{c}_0^T \mathbf{c}_1^T \ldots \mathbf{c}_{N-1}^T\right]^T$ and $\mathbf{n} = \left[\mathbf{n}_0^T \mathbf{n}_1^T \ldots \mathbf{n}_{N-1}^T\right]^T$ and also the the block-diagonal matrix $\mathbf{H}$ of size $NM_R \times NM_T$ is given by

$$\mathbf{H} = diag\left\{\mathbf{H}\left(e^{j2\pi(k/N)}\right)\right\}_{k=0}^{N-1}$$

It is assumed that the channel will be remain constant for one OFDM symbol, so the mutual information (in b/s/Hz) of the OFDM-based spatial multiplexing system is given by [9]

$$I = \frac{1}{N}\log\left[\det\left(\mathbf{I}_{NM_R} + \frac{1}{\sigma_n^2}\mathbf{H\Sigma H}\right)\right] \quad (15)$$

where $\mathbf{\Sigma}$ is the $NM_T \times NM_T$ covariance block-diagonal matrix of $\mathbf{c}$.

$$\mathbf{\Sigma} = diag\left\{\mathbf{\Sigma}_k\right\}_{k=0}^{N-1}$$

Here $\mathbf{\Sigma}_k$ is the $M_T \times M_T$ covariance block-diagonal matrix of $\mathbf{c}_k$. N is the normalization factor, as N data symbols are transmitted in one OFDM carrier. If CSI is available at receiver then Equation 15 can be written as (shown in [6])

$$I = \frac{1}{N}\sum_{k=0}^{N-1}\log\left[\det\left(\mathbf{I}_{M_R} + \rho\mathbf{H}\left(e^{j2\pi(k/N)}\right)\mathbf{H}^H\left(e^{j2\pi(k/N)}\right)\right)\right] \quad (16)$$

where $\rho = P/\left(M_T N \sigma_n^2\right)$ and P is the total transmitter power. If $\mathbf{h}(e^{j2\pi(k/N)})$ is the first column of $\mathbf{H}(e^{j2\pi(k/N)})$, then we can show that,

$$\mathbf{E}\left\{\mathbf{h}\left(e^{j2\pi(k/N)}\right)\mathbf{h}^H\left(e^{j2\pi(k/N)}\right)\right\} = \mathbf{R} \quad (17)$$

Note that the correlation matrix is independent of k. We can write

$$\mathbf{H}\left(e^{j2\pi(k/N)}\right) \sim \mathbf{R}^{1/2}\mathbf{H}_w + \bar{\mathbf{H}}$$

where $\mathbf{H}_w$ is $M_R \times M_T$ uncorrelated complex Gaussian matrix with zero mean and unit variance, $\mathbf{R} = \sum_{l=0}^{L-1}\mathbf{R}_l = \sum_{l=0}^{L-1}\mathbf{R}_l^{1/2}\mathbf{R}_l^{1/2}$ and $M_R \times M_T$ matrix $\bar{\mathbf{H}}$.
Hence I_k can be written as

$$I_k \sim \log\left[\det\left(\mathbf{I}_{M_R} + \rho\left(\mathbf{R}\mathbf{H}_w\mathbf{H}_w^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H\right)\right)\right] \quad (18)$$

Using SVD, the equation can also be written as

$$I_k \sim \log\left[\det\left(\mathbf{I}_{M_R} + \rho\left(\mathbf{U\Lambda U}\mathbf{H}_w\mathbf{H}_w^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H\right)\right)\right] \quad (19)$$

where $\mathbf{U}$ is a unitary matrix and $\mathbf{\Lambda} = diag\left\{\lambda_i(\mathbf{R})\right\}_{i=0}^{M_R-1}$ where $\lambda_i(\mathbf{R})$ denotes the i-th eigenvalue of $\mathbf{R}$.
Using $\mathbf{UH}_w \sim \mathbf{H}_w$ and Multiply $\mathbf{H}_w^H$ by $\mathbf{U}^H$ to obtain,

$$I_k \sim \log\left[\det\left(\mathbf{I}_{M_R} + \rho\left(\mathbf{U\Lambda}\mathbf{H}_w\mathbf{H}_w^H\mathbf{U}^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H\right)\right)\right] \quad (20)$$

Now using the property $det(\mathbf{I} + \mathbf{XY}) = det(\mathbf{I} + \mathbf{YX})$, $\mathbf{UU}^H = \mathbf{I}$, equation 20 can be written as

$$I_k \sim \log\left[\det\left(\mathbf{I}_{M_R} + \rho\left(\mathbf{\Lambda}\mathbf{H}_w\mathbf{H}_w^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H\right)\right)\right] \quad (21)$$

B. Ergodic capacity

The ergodic capacity is defined as

$$C = \mathcal{E}\left\{I\right\} = \mathcal{E}\left\{\frac{1}{N}\sum_{k=0}^{N-1} I_k\right\} \tag{22}$$

From equations 22 and 21

$$C = \mathcal{E}\left\{\frac{1}{N}\sum_{k=0}^{N-1}\log\left[\det\left(\mathbf{I}_{M_R} + \rho\left(\mathbf{\Lambda}\mathbf{H}_w\mathbf{H}_w^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H\right)\right)\right]\right\} \tag{23}$$

From equation 5 and $(1/M_T)\mathbf{H}_w\mathbf{H}_w^H \rightarrow \mathbf{I}_{M_R}$ for $M_T \gg M_R$, C can be written as

$$C = \log\left[\det\left(\mathbf{I}_{M_R} + \bar{\rho}(\mathbf{\Lambda} + (1/M_T)\bar{\mathbf{H}}\bar{\mathbf{H}}^H)\right)\right] \tag{24}$$

where $\bar{\rho} = M_T\rho = (P/(N\sigma_n^2))$..

IV. Simulation Results

Computer simulation results are presented to evaluate the capacities of MIMO-OFDM system under Rician fading. This section is divided into two parts, i.e. capacity analysis and the performance analysis of i.i.d. and spatially correlated MIMO-OFDM space time coded rician channel.

A. Capacity Analysis

The impact of the antenna number on the channel capacity is examined first selective-fading i.i.d. rician channel and is shown in figure 4. The capacity of the system increases with more antennas added to the system.

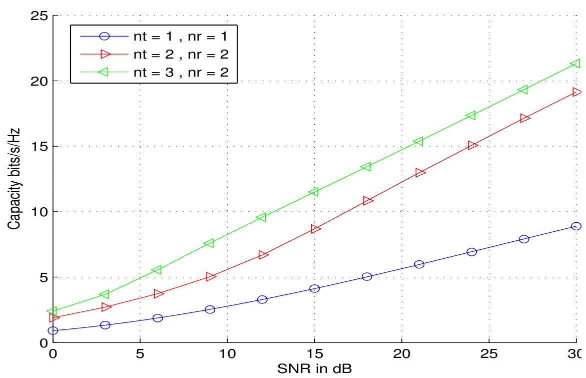

Fig. 4. Capacity versus SNR for selective-fading i.i.d. rician channel for $L = 4$ and $K = 3$.

While the calculated channel capacity per unit bandwidth as a function of SNR for spatially correlated selective-fading rician channel is shown in Figure 5. As expected, the capacity bounds increase monotonically as SNR increases. Only for extremely low SNRs, correlations can slightly improve the capacity. The comparison between correlated and uncorrelated simulation results for capacity analysis has been shown in Figure 6.

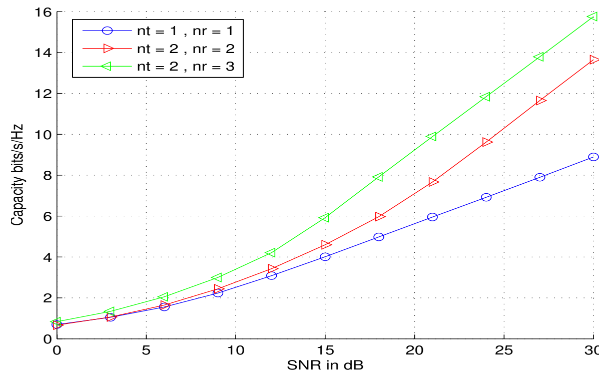

Fig. 5. Capacity versus SNR for spatially correlated selective-fading rician channel for $\rho = 0.2$, $L = 4$ and $K = 3$.

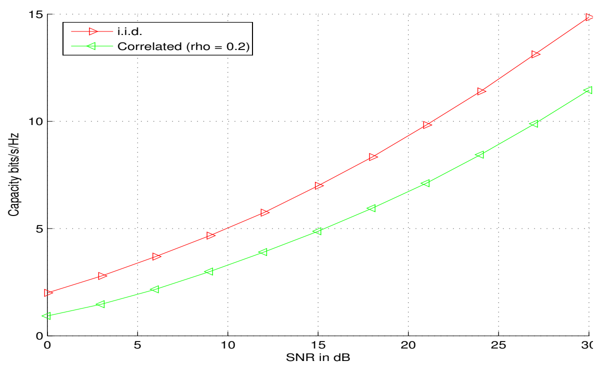

Fig. 6. Capacity versus SNR for (2×2) MIMO-OFDM system for $L = 4$ and $K = 3$

B. Performance Analysis

Now the performance of some MIMO-OFDM implementations with Rician fading model is presented with different antennas configurations. Here 16 tones used to transmit data. The simulated system employs a 16-point FFT, with BPSK modulation and an Alamoutis coding scheme with the transmission bit rate of 1 bit/(sHz) using one and two transmit antennas. Data is grouped into blocks of 3500 information bits, called words. Each word is coded into 16 symbols to form an OFDM block. Figure 7 compares the average BER for different number of transmit and receive antennas selective-fading i.i.d. rician channel. We assume that the transmit 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. The channel is considered to be quasi-static so that the channel coefficients are constant during each OFDM frame.

The performance of the Alamouti code over a Spatially correlated selective-fading rician channel is provided in Figure 8. As can be seen, the performance with two transmit antennas is much better than that of the system with one transmit antenna. At BER of 10^{-1}, the Alamouti code provides more than 8 dB gain. More importantly, due to the higher diversity gain of the Alamouti code, the gap increases for higher SNR values.

It was also noticed in Figure 9 how the performance

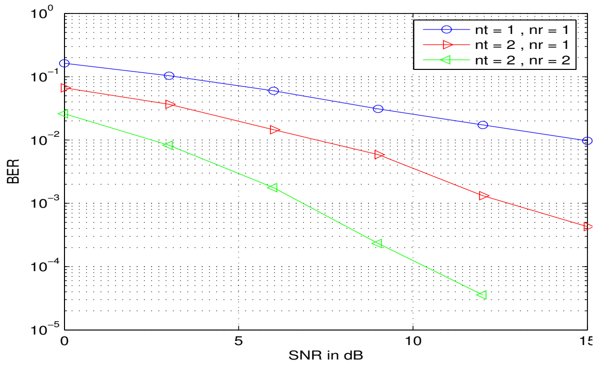

Fig. 7. BER plotted against SNR for orthogonal STBCs of selective-fading i.i.d. Rician channel with $K = 3$ and $L = 4$.

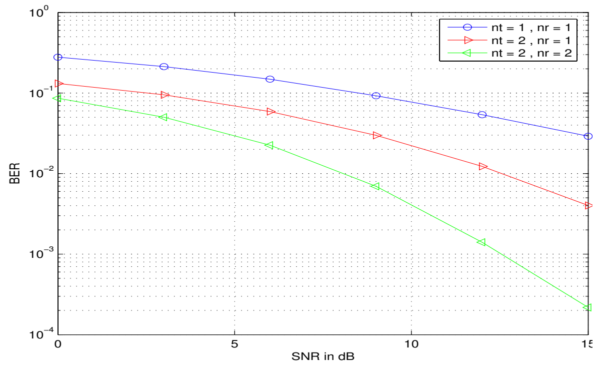

Fig. 8. BER plotted against SNR for orthogonal STBCs of spatially correlated selective-fading rician channel with $\rho = 0.2$, $K = 3$ and $L = 4$

increased with increasing K , due to a reduced probability of simultaneous fades. The channel thus becomes more robust for increasing K. However, often channels with high K correspond to channels with line of sight between transmitter and receive antenna array, and in these cases it is expected that the spatial correlation increases.

While Figure 10 shows the comparison between the performance of correlated and uncorrelated cases.

V. Conclusion

An analytical expression for ergodic capacity of MIMO-OFDM system has been derived under $(M_R \times M_T)$ rician fading channel with single-sided spatial fading correlation for the case where the channel is unknown at the transmitter and perfectly known at receiver. Based on the analytical results, we investigated the ergodic capacity as a function of the antenna configuration, correlation level and Rician K-factor.

A capacity and performance comparison of spatially correlated and i.i.d channels are performed for selective fading through simulation. The performance of Alamouti code over rician fading channels are also provided. It can be seen that by adding more antennas to the MIMO-OFDM system can significantly increase the channel capacity of the system and reduce with the increase of multi-paths (L). For the MIMO-OFDM systems with fixed antenna number and SNR value, the increase of the subchannel number has no contribution to the overall channel capacity.

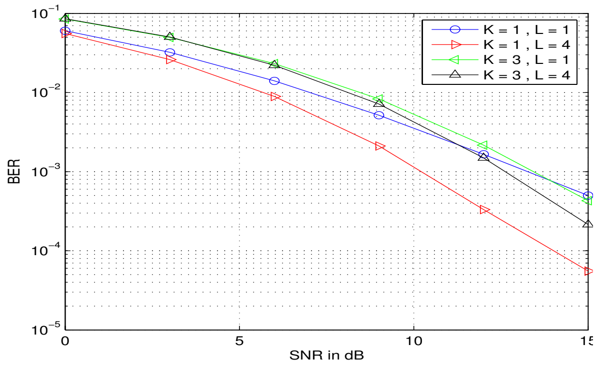

Fig. 9. BER plotted against SNR for orthogonal STBCs of spatially correlated selective-fading rician channel with (2×2) MIMO-OFDM system and $\rho = 0.2$.

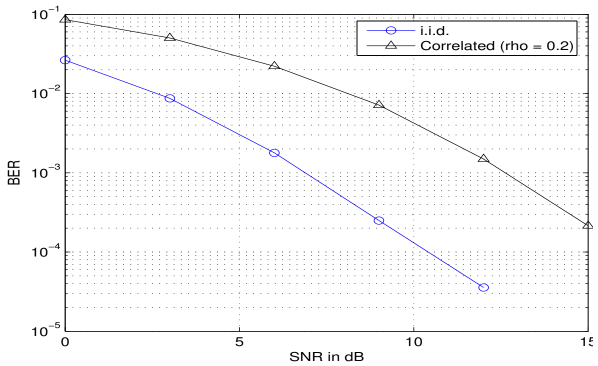

Fig. 10. BER versus SNR for (2×2) MIMO-OFDM system for $L = 4$ and $K = 3$

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