Performance Improvement Analysis of Wireless MIMO Channel in the Presence of Keyhole

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Abstract— **Wireless communication systems always demand higher data rates and better quality of service (QoS). Transmission reliability in a wireless channel with high path loss, time-varying multipath fading and power and bandwidth limitations, is a testing issue. Multiple-input multiple-output (MIMO) systems can reduce the effect of these channel interferences and achieve reliable signal transmission at high data rate. Space-time block code (STBC) is a coding scheme for the use of multiple transmits antennas providing a simple transmit diversity scheme. In certain MIMO fading environments, the offered channel capacity can be very low, where despite rich local scattering and uncorrelated transmit and receive signals, the system has a single degree of freedom. This effect has been termed as keyhole or pinhole effect. This contribution analyzes the average symbol error rate (SER) performance of MIMO systems employing orthogonal STBC with M-PSK constellations over fading channels in the presence of the keyhole. The Nakagami-*m* distribution has been considered for MIMO channel modeling. We derive the probability density function (PDF) of instantaneous signal-to-noise ratio (SNR) and an integral equation to calculate the average SER after space–time block decoding in such channels. Numerical results show that the keyhole significantly degrades the SER performance of the STBC in MIMO channels. The performance of such channels is a function of fading figure, *m* and diversity.**

Keywords— **Keyhole, multiple-input multiple-output system, Nakagami-*m* fading, space-time block codes, symbol error rate.**

I. INTRODUCTION

MULTIPLE-input multiple-output (MIMO) systems, which employ multiple antennas to transmit and receive data can increase the system capacity and improve transmission reliability [1]-[3]. They are able to provide diversity gain as well as spatial multiplexing gain. By transmitting multiple copies of data, a MIMO system can effectively combat the effects of fading.

The financial support of the Military Institute of Science and Technology (MIST), Bangladesh and Bangladesh Army is gratefully acknowledged by the authors.

In realistic MIMO fading environments, however, the existence of rank-deficient keyhole or pinhole can reduce the diversity gain and spatial multiplexing gain of the channel significantly. If two elements of transmitting and receiving antennas are surrounded by clutters, it will lead to uncorrelated Gaussian channel, which has high capacity. Now, if a screen with a small keyhole is placed in between the receiving and transmitting antennas, the radio wave will only propagate through the keyhole. It has been demonstrated through physical experiments that MIMO systems even with uncorrelated transmit and receive signals can only have a single or reduced degree of freedom in the presence of keyhole, thereby severely degrade the system performance [1]-[4].

In [5], Alamouti proposed a simple transmit diversity scheme for two transmit antennas. This scheme was then generalized to an arbitrary number of transmit antennas, known as STBC [6]. STBC is a coding scheme for the use of multiple transmits antennas providing a simple transmit diversity scheme [7]–[9]. These codes retain the property of having a simple maximum likelihood decoding algorithm based on linear processing at the receiver. Due to orthogonal structure of the STBCs, STBCs designed for n_T transmit with n_R receive antennas can achieve a full diversity of $n_T \times n_R$ in independent and identically distributed (i.i.d) MIMO fading channels. The Nakagami-*m* distribution has been considered for MIMO channel modeling since a wide range of fading channels from severe to moderate, can be modeled by using Nakagami-*m* distribution.

In this paper, we present the performance improvement analysis of orthogonal STBCs in MIMO fading channels with keyhole using Nakagami-*m* distribution. We derived a PDF expression for instantaneous SNR using inverse Fourier transform. Furthermore, an integral expression is derived to calculate the average SER in order to quickly evaluate the performance of STBC in such channels.

The rest of the paper is organized as follows. Section II presents the MIMO system model using STBCs. Section III describes fading channel with keyhole effect. An integral expression to calculate the average SER is derived in section IV. Our analytical results are shown in Section V. Section VI summarizes this paper.

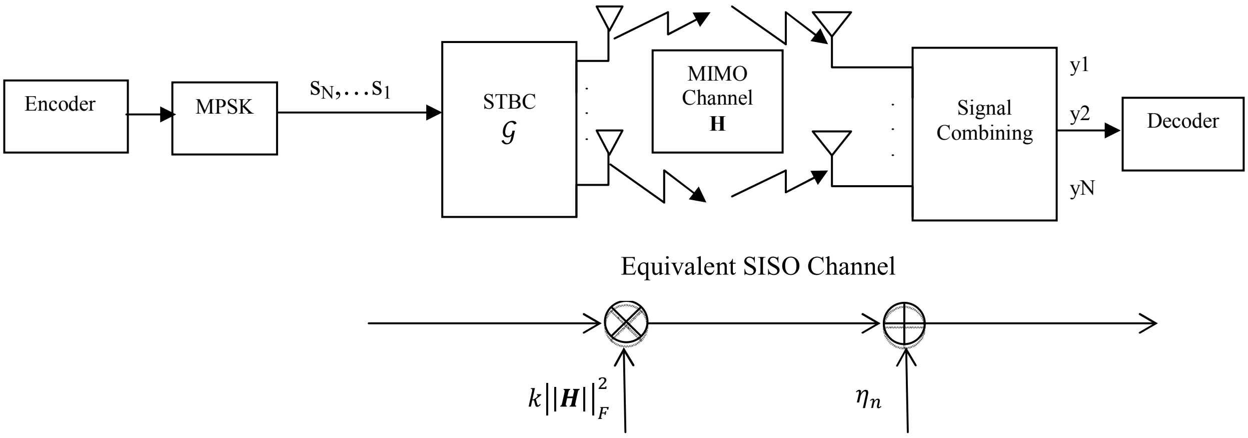

Figure 1. Space-time block coded MIMO system and Equivalent SISO model

II. SYSTEM MODEL

We consider a MIMO wireless communication system with n_T transmit and n_R receive antennas shown in Figure 1. The channel is assumed to be a quasi-static flat fading one, with keyhole effect and the channel state information (CSI) is known at the receiver but unknown at the transmitter. *Nb* information bits are mapped as symbols $s_1, s_2, \ldots. s_N$ which are selected from the M-PSK signal constellation, where $b=log_2M$. Then, $\{s_n\}_{n=1}^{N}$ are encoded by a STBC defined as a $p \times n_T$ column orthogonal transmission matrix $\mathcal{G}$

$$\mathcal{G} = \begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1n_T} \\ g_{21} & g_{22} & \cdots & g_{2n_T} \\ \vdots & \vdots & \ddots & \vdots \\ g_{p1} & g_{p2} & \cdots & g_{pn_T} \end{pmatrix} \quad (1)$$

where the entries g_{kj}, $k = 1, 2, \ldots. p$ and $j=1, 2, \ldots. n_T$ are linear combination of $s_1, s_2, \ldots. s_N$ and their conjugates [8], [9]. At each time slot *k*, signal $\{g_{kj}\}_{j=1}^{n_T}$ are transmitted simultaneously through n_T transmit antennas. Since *p* time slots are used to transmit *N* symbols, the rate of the code is $R=N/p$.

The STBC $\mathcal{G}_2$, first proposed by Alamouti in [5], is a one-rate code employing two transmitting antennas, defined by

$$\mathcal{G}_2 = \begin{pmatrix} s_1 & s_2 \\ -s_2{}^* & s_1{}^* \end{pmatrix} \quad (2)$$

For three and four transmit antennas the STBCs are represented by $\mathcal{G}_3$ and $\mathcal{G}_4$ [8], where the rate of $\mathcal{G}_3$ and $\mathcal{G}_4$ are half. The orthogonal space–time block encoding and decoding (signal combining) transform a MIMO fading channel into an equivalent single-input single-output (SISO) Gaussian channel with a path gain of the squared Frobenius (or Hilbert–Schmidt) norm of the channel matrix [10]–[13]. In [14], it is also shown that the orthogonal STBCs are optimal in terms of the SNR.

The signal received by the *i*th antenna in the *k*th time slot is given by [2]

$$r_k^{(i)} = \sum_{j=1}^{n_T} h_{ij} g_{kj} + n_k^{(i)} \quad (3)$$

where $n_k^{(i)}$ is a zero-mean complex Gaussian noise with variance $N_0/2$ per dimension, g_{kj} is the signal transmitted by *j*th antenna at time slot *k* and h_{ij} is the *(i, j)*th entry of channel matrix **H**. The average energy of the symbols transmitted from each antenna is assumed to be E_s/n_T so that the average power of the received signal at each receive antenna is equal to $\left(\frac{E_s}{n_T}\right) \sum_{j=1}^{n_T} E\left[\left|h_{ij}\right|\right]^2 = E_s$ and the SNR per receive antenna is E_s/N_0. With perfect CSI, the ML receiver computes the decision metric [9]

$$D = \sum_{k=1}^{p} \sum_{i=1}^{n_R} \left| r_k^{(i)} - \sum_{j=1}^{n_T} h_{ij}\, g_{kj} \right|^2 \quad (4)$$

over all code words and decides in favor of the codeword that minimizes the sum *D*.

III. CHANNEL MODEL

A. Fading

The most troublesome and frustrating phenomenon in receiving radio signals having variations in signal strengths, is known as fading. There are several conditions that can produce fading. Usually fading is a result of multipath propagation. When a received signal experiences fading during transmission, both its amplitude and phase fluctuate over time. For coherent modulations, the fading effects can severely degrade performance unless measures are taken to compensate for them at the receiver.

The multipath fading is classified as large scale fading and small scale fading. Small scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes in the spatial position between transmitter and receiver. Small scale fading can be divided as flat fading, frequency selective fading, fast fading and slow fading. Out of those, flat fading offers severe fading situation where as frequency selective fading causes the signal distortion.

To design and investigate the performance of digital communication systems, various statistical models for multipath fading channels are developed. Nakagami-*m* distribution is a widely used statistical model for fading envelopes of signals in urban and sub-urban environments due to its great versatility. With a parameter *m* ranging from 0.5 to infinite, it can model different fading scenarios from severe to moderate. The PDF of Nakagami-*m* distribution is given by [15]

$$p_R(r) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{\frac{-mr^2}{\Omega}} \quad (5)$$

$$r \geq 0, \qquad m \geq 0.5$$

where the parameter, Ω and the fading figure, *m* are

$$\Omega = E[R^2], \qquad m = \frac{\Omega^2}{E[(R^2 - \Omega^2)]}$$

and $\Gamma(n)$ is the standard Gamma function

$$\Gamma(n) = \int_0^\infty exp(-x)\, x^{n-1}\, dx \quad (6)$$

B. Keyhole

If two elements of transmitting and receiving antennas are surrounded by clutters, it will lead to uncorrelated Gaussian channel, which has high capacity. Now, if a screen with a small keyhole is placed in between the receiving and transmitting antennas, the radio wave will only propagate through the keyhole [1].

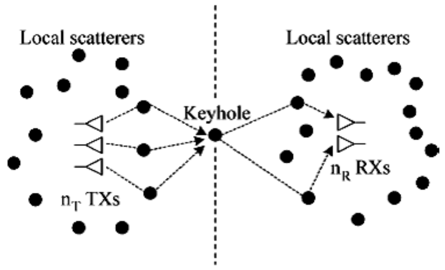

Figure 2. Keyhole MIMO Channel

It has been demonstrated through physical experiments that MIMO systems even with uncorrelated transmit and receive signals can only have a single or reduced degree of freedom. In this case the channel matrix **H** is a product of a complex Gaussian column vector and complex Gaussian row vector as shown in (7)

$$\mathbf{H} = \begin{pmatrix} \beta_1 e^{j\vartheta_1} \\ \beta_2 e^{j\vartheta_2} \\ \vdots \\ \beta_{n_R} e^{j\vartheta_{n_R}} \end{pmatrix} \begin{pmatrix} \alpha_1 e^{j\varphi_1} & \alpha_1 e^{j\varphi_1} & \ldots & \alpha_{n_T} e^{j\varphi_{n_T}} \end{pmatrix} \quad (7)$$

In (7), $\{\alpha_j e^{j\varphi_j}\}_{j=1}^{n_T}$ and $\{\beta_i e^{j\varphi_i}\}_{i=1}^{n_R}$ describe the rich scattering at transmit and receive arrays, respectively. The (*i, j*) th entry h_{ij} of **H** represents a complex channel coefficient from the j^{th} transmit antenna to the i^{th} receive antenna. We assume that $\{\alpha_j\}_{j=1}^{n_T}$ and $\{\beta_i\}_{i=1}^{n_R}$ are i.i.d. Nakagami-*m* variates with fading severity parameters m_T and m_R respectively, namely,

$$p_{\alpha_j}(\alpha) = \frac{2}{\Gamma(m_T)}\left(\frac{m_T}{\Omega_T}\right)^{m_T} \alpha^{2m_T-1} e^{\frac{-m_T\alpha^2}{\Omega_T}}$$

$$\alpha \geq 0,\ m_T \geq 0.5,\ j = 1, 2 \ldots .n_T \quad (8)$$

$$p_{\beta_i}(\beta) = \frac{2}{\Gamma(m_R)}\left(\frac{m_R}{\Omega_R}\right)^{m_R} \beta^{2m_R-1} e^{\frac{-m_R\beta^2}{\Omega_R}}$$

$$\beta \geq 0,\ m_R \geq 0.5,\ i = 1, 2 \ldots .n_R \quad (9)$$

where $\Omega_T = E[\alpha_j^2]$, $\Omega_R = E[\beta_i^2]$ and $\Gamma(.)$ is the gamma function. All of the channel phase shifts $\{\varphi_j\}_{j=1}^{n_T}$ and $\{\vartheta_i\}_{i=1}^{n_R}$ are assumed to be independent and uniformly distributed over $[0,2\pi]$. Furthermore, we assume that the keyhole ideally reradiates the captured energy, like transmit and receive scatterers, and that each entry of **H** has a unit power, i.e., $E\left[\left|h_{ij}\right|^2\right] = \Omega_T.\Omega_R = 1$ for all $i = 1, 2 \ldots .n_R$ and $j = 1, 2 \ldots .n_T$. All of $\alpha_j e^{j\varphi_j}$ and $\beta_i e^{j\varphi_i}$ are independent and all entries of **H** are uncorrelated, but rank (**H**) =1.

IV. SER ANALYSIS

Let E_{Tot} be the total average energy of a block, i.e. $E_{Tot} = E[\|\mathcal{G}\|_F^2] = p.E_s$ where $\|\mathcal{G}\|_F^2$ is the squared Frobenius norm of the matrix $\mathcal{G}$. From the column orthogonal property of the matrix $\mathcal{G}$, E_{Tot} can be also written as

$$E_{Tot} = E[tr(\mathcal{G}\mathcal{G}^T)]$$

$$= E\left[tr\left\{\left(\mathcal{K}\sum_{n=1}^{N}|s_n|^2\right)I\right\}\right] = n_T.\mathcal{K}.N.E_0$$

where I is the $n_T \times n_T$ identity matrix and $\mathcal{K}$ is a constant depending on the matrix $\mathcal{G}$. For example, $\mathcal{K}$=1 for $\mathcal{G}_2$ and $\mathcal{K}$=2 for $\mathcal{G}_3$ and $\mathcal{G}_4$. We get the average energy of the constellation as

$$E_0 = \frac{p.E_s}{n_T.\mathcal{K}.N} = \frac{E_s}{n_T.\mathcal{K}.R}$$

The instantaneous SNR per symbol after space-time block decoding is [2]

$$\gamma_{STBC} = \frac{k^2\|\boldsymbol{H}\|_F^4 E_0}{k^2\|\boldsymbol{H}\|_F^2 N_0} = \frac{\|\boldsymbol{H}\|_F^2 E_s}{n_T R N_0} \quad (10)$$

where $\|H\|_F^2$ is the squared Frobenious norm of channel matrix **H**. We can write the squared Frobenious norm of the channel matrix as

$$\|\boldsymbol{H}\|_F^2 = \sum_{i=1}^{n_R}\sum_{j=1}^{n_T}\alpha_j^2.\beta_i^2 = \sum_{j=1}^{n_T}\alpha_j^2\sum_{i=1}^{n_R}\beta_i^2$$

It is evident that, since α_j and β_i are Nakagami-*m* distributed, α_j^2 and β_i^2 follow the Gamma distribution, i.e., $\alpha_j^2 \sim \square(\frac{\Omega_T}{m_T}, m_T)$ and $\beta_i^2 \sim \square(\frac{\Omega_R}{m_R}, m_R)$.

The MGF of $\|H\|_F^2$ is [2]

$$\phi\|\mathbf{H}\|_F^2(s) = {}_2F_0\left(m_T n_T, m_R n_R; ; -\frac{s}{m_T m_R}\right) \quad (11)$$

where ${}_pF_q\left(a_1, a_2, \ldots a_p;\ b_1, b_2, \ldots b_q; x\right)$is the generalized hypergeometric function.

From (10) and (11), the MGF of γ_{STBC} for keyhole MIMO channels can be written as [2]

$$\phi_{\gamma STBC}^{Keyhole}(s) \triangleq \int_0^\infty e^{-s\gamma} . p_{\gamma STBC}^{keyhole}(\gamma) d\gamma$$

$$= {}_2F_0\left(m_T n_T, m_R n_R; ; -\frac{s\frac{E_S}{N_0}}{m_T m_R n_T R}\right) \quad (12)$$

where $p_{\gamma STBC}^{keyhole}(\gamma)$ is the PDF of instantaneous SNR after space-time block decoding for keyhole Nakagami-*m* fading channels.

Now, (12) can be rewritten as

$$F_\phi(j\omega) = {}_2F_0\left(m_T n_T, m_R n_R; ; -\frac{j\omega\frac{E_S}{N_0}}{m_T m_R n_T R}\right) \quad (13)$$

By performing inverse Fourier transform of (13) we can derive the PDF of γ_{STBC} for keyhole MIMO channels as

$$p_{\gamma STBC}^{keyhole}(\gamma) = IFT\{F_\phi(j\omega)\}$$

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} F_\phi(j\omega) e^{-j\omega} d\omega \quad (14)$$

The conditional SER for M-PSK signal is given by [16], [17]

$$P_S^{MPSK}(E|\gamma) = \frac{1}{\pi} \int_0^{\pi - \frac{\pi}{M}} \exp\left(-\frac{\gamma g_{MPSK}}{\sin^2\theta}\right) d\theta \quad (15)$$

where $g_{MPSK} = \sin^2\left(\frac{\pi}{M}\right)$. Averaging (15) over the PDF $p_{\gamma STBC}^{Keyhole}(\gamma)$, the average SER of STBC with M-PSK modulation over keyhole Nakagami-*m* fading channel is given by

$$P_{keyhole}^{MPSK}(E) = \frac{1}{\pi} \int_0^\infty \int_0^{\pi - \frac{\pi}{M}} \exp\left(-\frac{\gamma g_{MPSK}}{\sin^2\theta}\right) p_{\gamma STBC}^{keyhole}(\gamma) d\theta d\gamma \quad (16)$$

V. RESULT AND DISCUSSION

In this section, we provide the results of our analysis for orthogonal STBC in MIMO system with keyhole Nakagami-*m* fading channel. The information source is encoded using STBC $\mathcal{G}_2$ and ML detection scheme is used at the receiver. In all analysis we have set m_T=m_R=*m*.

Figure 3 plots the average SER versus instantaneous SNR per antenna for QPSK (M=4) modulation with varying fading figure *m* (*m*=0.5, 1, 2, 4, 8, 16). We found that SER decreases with the increase of fading figure, *m*.

For a particular SER the value of instantaneous SNR at different fading figures are plotted in Figure 4. For a particular value of average SER, with the increase of fading figure, *m*, the required instantaneous SNR is reduced, thereby improving the system performance.

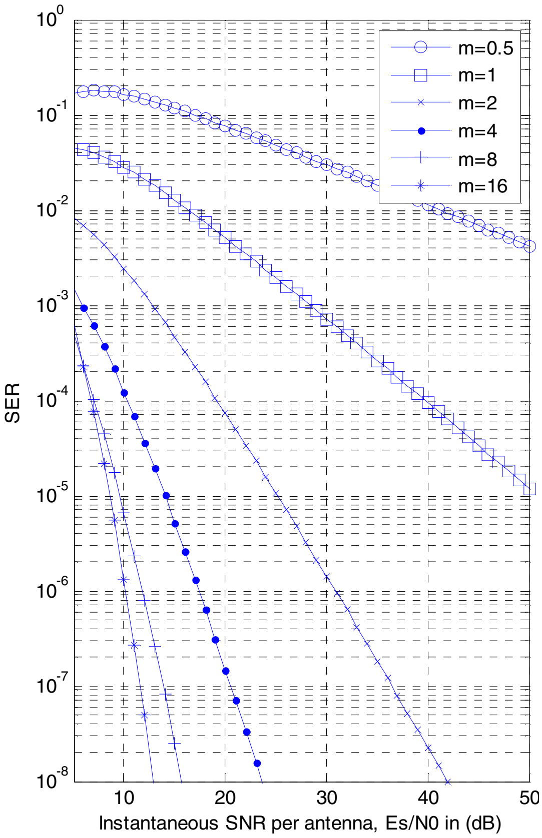

Figure 3. SER versus Instantaneous SNR for QPSK Modulation with varying Fading Figure, *m* (*m*=0.5, 1, 2, 4, 8, 16)

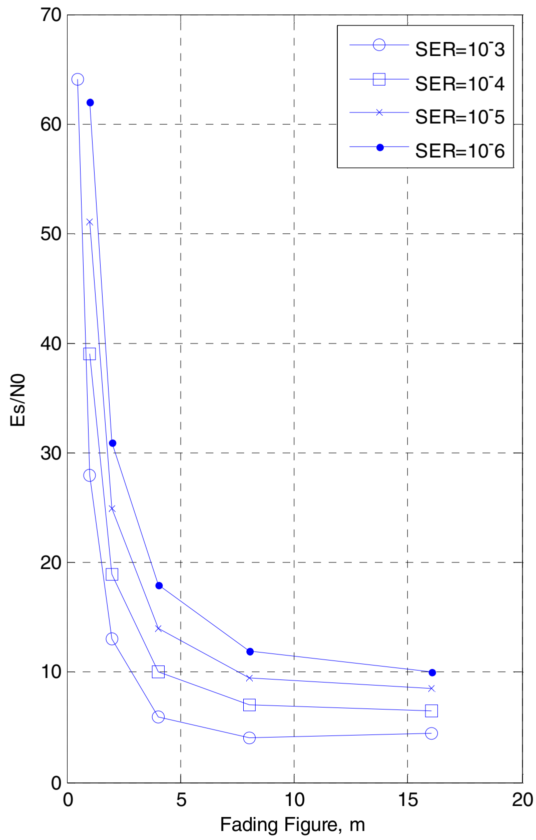

Figure 4. Instantaneous SNR versus Fading Figure, *m* for varying SER

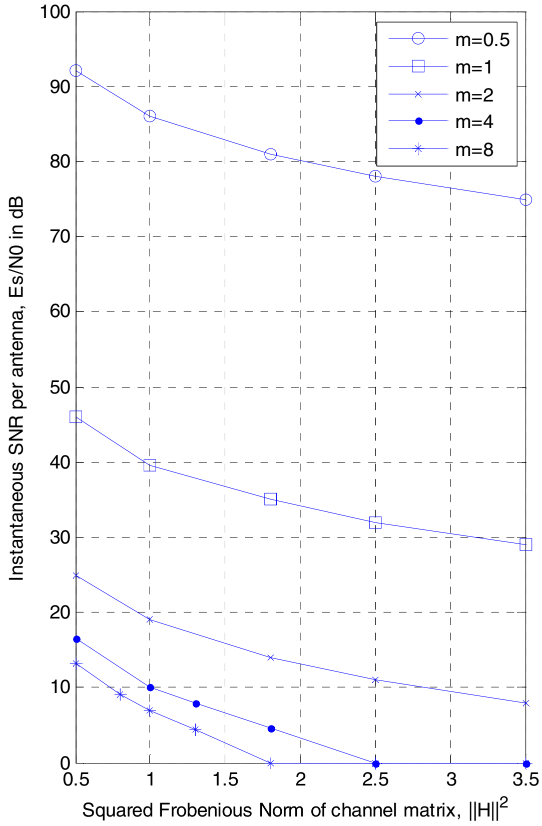

Figure 5. Instantaneous SNR versus Squared Frobenious Norm of Channel Matrix H for different Fading Figures at SER=10^{-3}

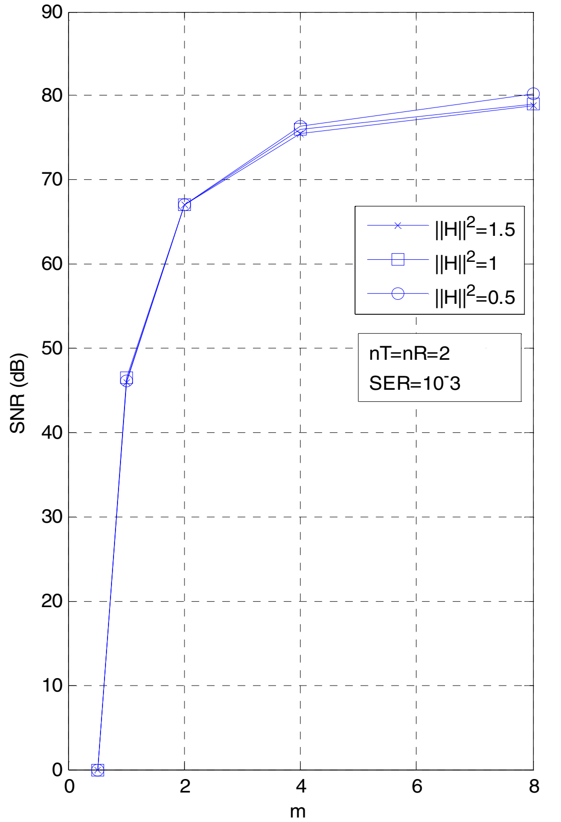

Figure 7. Improvement in SNR (dB) versus Fading Figure, *m* for varying ||H||^2

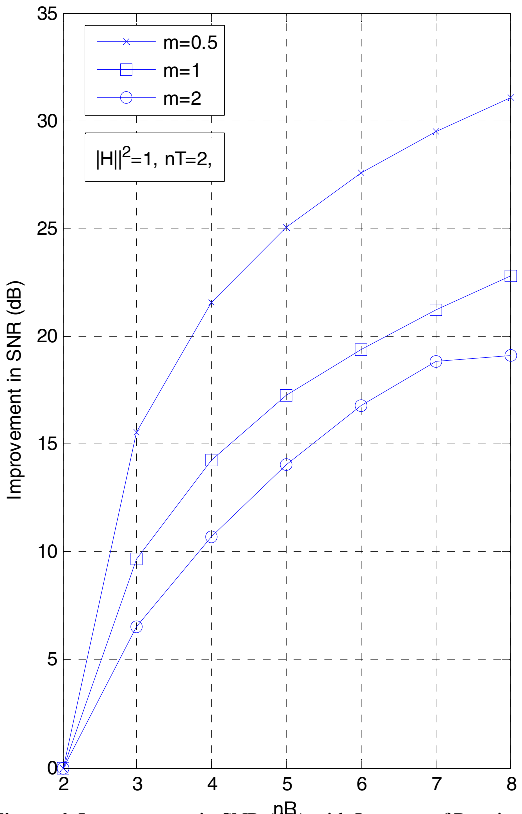

Figure 6. Improvement in SNR (dB) with Increase of Receive Antennas (Diversity) for varying Fading Figure, *m*

Figure 5 plots the instantaneous SNR versus squared Frobenious norm of channel matrix **H** for different fading figures. Here as we increased the value of $\|\boldsymbol{H}\|_F^2$, instantaneous SNR reduces for a particular fading figure, *m*. We considered the average SER of 10^{-3} for this case.

We have plotted the improvement in instantaneous SNR against number of transmit and receive antennas (diversity) in Figure 6 for a particular value of fading figure, *m*. We find that a significant improvement in performance of MIMO channel can be achieved by diversity even in the presence of keyhole. However, no significant improvement of performance is marked with the change of squared Frobenious norm of channel matrix **H** as shown in Figure 7.

VI. CONCLUSION

We investigated the effect of keyhole, which makes a MIMO channel exhibit uncorrelated spatial fading between antennas but a poor rank property, on the SER of STBC. The fading between each pair of transmit and receive antennas for keyhole channels was assumed to be characterized by a double Nakagami-*m* distribution. We derived the PDF of instantaneous SNR after space–time block decoding and single finite-range integral expression for the average SER of the STBC with M-PSK constellations over keyhole Nakagami-*m* fading channels. Furthermore, we examined the effect of keyholes on the severity of fading and performance of STBC in Nakagami-*m* fading channels.

We find that significant improvement in the performance of MIMO channel can be achieved by diversity even in the presence of keyhole. However, no significant improvement in performance is marked with the change of squared Frobenious norm of channel matrix **H**.

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