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## LOS ANGELES

*Wireless Technologies for Global Security*

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# Combining Beamforming with Alamouti Scheme for Multiuser MIMO Communications

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*Abstract*—**We combine optimum receive beamforming with the Alamouti space-time block code (STBC) transmission and modify the decoding process. In a multiuser multiple-input multiple-output (MIMO) communications scenario, the beamformer suppresses co-channel interference by maximizing the uplink signal-to-noise-plus-interference-ratio (SINR). It is shown that the beamforming process increases the bit-error-rate (BER) performance and maximizes the available uplink channel capacity for each user in the presence of co-channel interference (CCI). The ergodic capacity of a conventional 2-by-1 Alamouti scheme is also increased from 3.2 to 4 bits/s/Hz by adding one receive antenna.**

***Keywords-Beamforming, Alamouti space-time block code (STBC), multiple-input multiple-output (MIMO), Wishart distribution***

## I. INTRODUCTION

During the migration from the second generation (2G) systems to the third generation (3G) systems, great efforts have been directed toward the development of the modulation, coding, and protocols for the 2G Systems, such as the code division multiple access (CDMA) with IS-95, the time division multiple access (TDMA) with IS-136 and the GSM. However, these techniques have been exhausted to the limit due to the large number of subscribers within the limited channel capacity. Antennas have gained much interest among researchers. The smart antenna system, in the form of adaptive arrays, can mitigate three major impairments caused by wireless channels: *fading*, *delay spread*, and *cochannel interferences (CCI)*.

As the earliest implementation of smart antenna technologies, diversity array antennas have played important roles in mitigating the devastating effect of the multipath fading to wireless communication links. Recent studies on multipath propagation mechanism have shown that the multipath phenomenon achieves an information-theoretic channel capacity that increases with the number of array antenna elements [1]. In rich multipath environments, multiple transmit and receive antennas are installed at both transmitters and receivers to construct multiple-input multiple-output (MIMO) channels. Transmitting space-time block codes (STBCs) through a MIMO channel dramatically increases the data rate of the transmission over wireless channels [2]. Among various STBC codes developed recently, the Alamouti STBC [3] has been adopted extensively as an effective transmit diversity technique because of its computational simplicity.

Due to the frequency reuse, multiple access schemes and multiuser communications wireless channels are impaired with CCI. Beamforming using smart antennas has long been recognized as an effective means for suppressing CCI to improve the spectrum efficiency. In the context of MIMO communications, the meaning of "beamforming" has been extended to include combining independent signals output from diversity array antennas at both transmitters and receivers. In [4], multiuser MIMO communications are realized with the precise channel state information (CSI). However, the joint optimization at both the BS and multiple MSs is required and matrix diagonalization and decomposition are involved. Dighe et al. [5] assume that the number of the transmit antennas of multiple users (the desired users and interferers) is larger than the number of the receive antennas. The CCI is suppressed by maximizing the output signal-to-interference-plus-noise ratio (SINR) jointly at MS transmitters and the BS receiver. Capon beamforming is applied in [6], where data streams from a MS's two transmit antennas are treated independently as desired signals. The receiver minimizes the output power and passes each individual data steam with unit gain. The complexity increases when STBCs are transmitted with more transmit antennas at each MS.

To combine the CCI suppression ability of beamforming techniques with the Alamouti STBC transmission and achieve the receiver computational simplicity, we serially concatenate optimum beamforming with the linear Alamouti decoding process. Specially, we consider the scenario where all the MSs transmit Alamouti STBC with two transmit antennas and the CSI of CCI is unknown to the receiver. Employed with an increased number of receive antennas the BS beamforming process maximizes the output SINR to suppress CCI. The coantenna interference (CAI) is suppressed at the STBC decoder. Since, the technique preserves algebraic structure of the Alamouti STBC and sustain the orthogonally of the virtual MIMO channel in the presence of beamforming, the maximum-likelihood (ML) decoding process is achieved simple linear processing. The concatenation provides significant BER improvement and channel gain in comparison with the conventional Alamouti scheme.

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## II. SYSTEM MODEL AND ASSUMPTIONS

In the following mathematical exposition, superscripts $(\bullet)^T$, $(\bullet)^*$, and $(\bullet)^H$ denote transpose, complex conjugate, and conjugate-transpose, respectively. We consider a scenario where there are $M$ number of MSs communicate synchronously with a common BS as shown in Fig. 1. Each MS has two transmit antenna $Tx = 2$ and the BS has $Rx$ number of receive antennas. The Rayleigh block fading uplink channel from the desired MS, say MS-1, to the BS is modeled as an $Rx$–by–2 dimensional matrix:

$$\mathrm{H}^{(1)} = \begin{bmatrix} h_{1,1}^{(1)} & h_{2,1}^{(1)} & \cdots & h_{Rx,1}^{(1)} \\ h_{1,2}^{(1)} & h_{2,2}^{(1)} & \cdots & h_{Rx,2}^{(1)} \end{bmatrix}^T \tag{1}$$

where $h_{i,j}^{(1)}$ denotes the Rayleigh fading CSI of the wireless uplink between the $j$th transmit antenna at the MS-1 and the $i$th receive antenna the BS. Each entry in the channel matrix is modeled as a statistically independent and identically distributed (i.i.d.) zero-mean complex Gaussian variable with unit variance.

An Alamouti STBC word [3] sent over MS-$m$ two transmit antennas during two symbol epochs [the first column at $n$T and the second column at $(n+1)T$], where $n$ is the discrete time index and $T$ is the symbol duration, is represented as:

$$\mathbf{S}^{(m)} = \begin{bmatrix} s_1^{(m)} & -\left\{s_2^{(m)}\right\}^* \\ s_2^{(m)} & \left\{s_1^{(m)}\right\}^* \end{bmatrix}. \tag{2}$$

The time argument is dropped for the simplicity of mathematical exposition. It is understood that the variables are in fact dependent on the discrete time $n$. The Alamouti code word has the property as:

$$\mathrm{E}\left[\mathbf{S}^{(m)}\left\{\mathbf{S}^{(m)}\right\}^H\right] = 2E_S\mathbf{I}_2 \tag{3}$$

where $E_S$ is the symbol energy. $\mathbf{I}_2$ represents a 2−by−2 dimensional identity matrix, and E[•] is the expected value operator. The noise sample collected at those $Rx$ receive antennas at the BS over two symbol epochs are represented with an $Rx$-by-2 dimensional matrix $\mathbf{N}$ with each entry modeled as an i.i.d. zero-mean complex Gaussian variable with variance $\sigma^2$ . The total transmitted signal power at each MS transmitter is fixed at value $2E_S$. The signal-to-noise ratio (SNR) is defined as $2E_S/\sigma^2$. Signal samples on those $Rx$ receive antennas at the BS over two symbol epochs are expressed with an $Rx$-by-2 dimensional matrix:

$$\mathbf{X} = \underbrace{\mathbf{H}^{(1)}\mathbf{S}^{(1)}}_{\textit{desired signals}} + \underbrace{\sum_{m=2}^{M}\mathbf{H}^{(m)}\mathbf{S}^{(m)} + \mathbf{N}}_{\textit{unwante dsignals}} \tag{4}$$

where we assume that signals from MS-1 are the desired signals while those from other MSs are CCI. Please note that CSI of CCI is unknown at the receiver. The task of the beamforming process is to minimize the power of the unwanted signals. In (4), we have defined the two signal streams from MS-1 as the desired signals. Although these two streams pose CAI to each other [7, pp. 358-360], they are well separated at the linear decoding stage as we show in the following section.

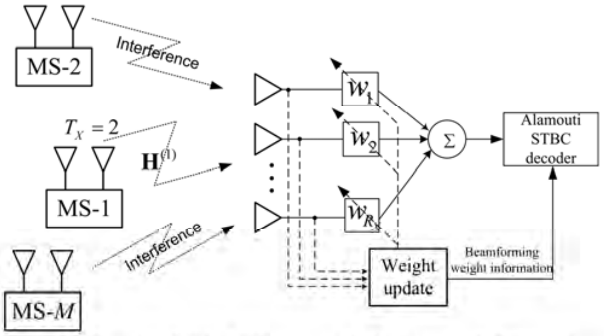

Figure 1. Functional block diagram of the proposed BS receiver structure that serially concatenates beamforming with Alamouti STBC decoder.

## III. BEAMFORMING AND DECODING PROCESS

The output SINR at the beamformer is defined as:

$$\gamma^{(1)} = \frac{\left\{\mathbf{w}^{(1)}\right\}^H \mathbf{R}_s \mathbf{w}^{(1)}}{\left\{\mathbf{w}^{(1)}\right\}^H \mathbf{R}_{ni} \mathbf{w}^{(1)}} \tag{5}$$

where the $Rx$-by-1 beamforming weight vector $\mathbf{w}^{(1)}$ at the receive antennas is constructed as:

$$\mathbf{w}^{(1)} = \begin{bmatrix} w_1^{(1)} & w_2^{(1)} & \cdots & w_{Rx}^{(1)} \end{bmatrix}^T. \tag{6}$$

In (5), the signal correlation matrix and the interference plus noise (unwanted signal) correlation matrix are expressed, respectively as:

$$\mathbf{R}_s = \mathrm{E}\left[\mathbf{H}^{(1)}\mathbf{S}^{(1)}\left\{\mathbf{H}^{(1)}\mathbf{S}^{(1)}\right\}^H\right] = 2E_S\mathbf{H}^{(1)}\left\{\mathbf{H}^{(1)}\right\}^H, \tag{7}$$

and

$$\begin{aligned}\mathbf{R}_{ni} &= \mathrm{E}\left[\left\{\sum\nolimits_{m=2}^{M}\mathbf{H}^{(m)}\mathbf{S}^{(m)} + \mathbf{N}\right\}\left\{\sum\nolimits_{m=2}^{M}\mathbf{H}^{(m)}\mathbf{S}^{(m)} + \mathbf{N}\right\}^H\right] \\ &= 2E_S\sum\nolimits_{m=2}^{M}\mathbf{H}^{(m)}\left\{\mathbf{H}^{(m)}\right\}^H + 2\sigma^2\mathbf{I}_{Rx}.\end{aligned} \tag{8}$$

From (5) we observe that the beamforming problem is in essence a generalized Rayleigh quotient problem and its value is bounded by the maximum eigenvalue $\lambda_{\max}$ and the minimum eigenvalue $\lambda_{\min}$ of $\mathbf{R}_{ni}^{-1}\mathbf{R}_s$ [8, pp. 177-181]. To maximize the output SINR at the beamformer $\mathbf{w}^{(1)}$ is chosen as the eigenvector corresponding to the maximum eigenvalue of $\mathbf{R}_{ni}^{-1}\mathbf{R}_s$. In the presence of the beamforming, an equivalent 1–by–2 dimensional vector channel is formed at the BS $Rx$ receive antennas for MS-1 as:

$$\mathbf{g}^{(1)} = \begin{bmatrix} g_1^{(1)} & g_2^{(1)} \end{bmatrix} = \left\{\mathbf{w}^{(1)}\right\}^H \mathbf{H}^{(1)}. \tag{9}$$

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Exploiting the algebraic structure of the Alamouti STBC word [3], the virtual MIMO channel over two symbol epochs is constructed as:

$$\mathbf{G}^{(1)} = \begin{bmatrix} g_1^{(1)} & g_2^{(1)} \\ \left\{g_2^{(1)}\right\}^* & -\left\{g_1^{(1)}\right\}^* \end{bmatrix}. \tag{10}$$

It is obvious that in the presence of beamforming, the virtual Alamouti MIMO channel still preserves the complex-orthogonal property. By virtue of this orthogonally the decoding process is achieved with simple linear processing.

At the Alamouti STBC decoder, the linear processing process produces two outputs for the ML detection of symbols $s_1^{(1)}$ and $s_2^{(1)}$. The process is formulated as:

$$\begin{bmatrix} \widehat{s_1^{(1)}} \\ \widehat{s_2^{(1)}} \end{bmatrix} = \left\{\mathbf{G}^{(1)}\right\}^{-1} \begin{bmatrix} y_1 \\ y^*_2 \end{bmatrix} \tag{11}$$

where $\mathbf{y}$ is a 2-by-1 dimensional signal vector output at the beamformer over two symbol epochs as:

$$\mathbf{y} = [y_1 \quad y_2]^T = \left\{\mathbf{w}^{(1)}\right\}^H \mathbf{X}. \tag{12}$$

It can be easily proved that the output SINR at the beamformer for the uplink of MS-1 can be expressed as:

$$\gamma^{(1)} = \frac{2E_S\left(\left|g_1^{(1)}\right|^2 + \left|g_2^{(1)}\right|^2\right)}{\left\{\mathbf{w}^{(1)}\right\}^H \mathbf{R}_{ni} \mathbf{w}^{(1)}}. \tag{13}$$

Following the approach as presented in [9, p. 441], it is also easy to prove that the SINR at the Alamouti STBC decoder for each of the two data symbols is equal to $\gamma^{(1)}$. This infers that CCI suppression is fulfilled at the beamformer whereas the decoding process does not bring any SINR advantage, but separates two data streams from MS-1 to suppress CAI.

## IV. PERFORMANCE EVALUATION

In this section, we study the bit-error-rate (BER) performance and the achieved MIMO channel capacity. Monte-Carlo simulation is also executed to compare with the analytical analysis results. BPSK is employed as the modulation scheme.

### *A. BER Performance*

After the STBC decoding processing, the receiver performance ML symbol detection. Given the probability density function (pdf) $f_{\gamma^{(1)}}(v)$ of the output SINR $\gamma^{(1)}$ for MS-1, the average BER is obtained by calculating [9, pp.299]:

$$P_e^{(1)} = \frac{1}{2}\int_{-\infty}^{\infty} \operatorname{erfc}\left(\sqrt{v}\right) f_{\gamma^{(1)}}(v)\,\mathrm{d}v. \tag{14}$$

Under the assumption that the MIMO channel undergoes Rayleigh fading, the two channel correlation matrices, $\mathbf{H}^{(1)}\{\mathbf{H}^{(1)}\}^H$ and $\sum_{m=2}^{M} \mathbf{H}^{(m)}\left\{\mathbf{H}^{(m)}\right\}^H$ follow complex the Wishart distribution as:

$$\mathbf{H}^{(1)}\left\{\mathbf{H}^{(1)}\right\}^H \sim \mathcal{CW}_{Rx}(Tx, \mathbf{I}_{Rx}), \tag{15}$$

$$\sum_{m=1}^{M} \mathbf{H}^{(m)}\left\{\mathbf{H}^{(m)}\right\}^H \sim \mathcal{CW}_{Rx}(Tx(M-1), \mathbf{I}_{Rx}), \tag{16}$$

Both distributions have the same dimension of $Rx$, but different ranks of $Tx$ and $Tx(M\text{ -}1)$, respectively. When $M = 2$, $Tx = 2$, and $Rx = 1$, it is a conventional Alamouti scheme where two transmit antennas are employed to transmit Alamouti STBC and one receive antennas are utilized to receive the signals and there is not CCI [3]. In this case, the output SINR at the beamformer is:

$$\gamma^{(1)} = \frac{2E_S\left\{\mathbf{w}^{(1)}\right\}^H \mathbf{H}^{(1)}\left\{\mathbf{H}^{(1)}\right\}^H \mathbf{w}^{(1)}}{2\sigma^2\left\{\mathbf{w}^{(1)}\right\}^H \mathbf{w}^{(1)}} = \frac{E_S}{\sigma^2}\lambda_{\max}. \tag{17}$$

where the pdf of $\lambda_{\max}$ of $\mathbf{H}^{(1)}\{\mathbf{H}^{(1)}\}^H$ is given as [10]:

$$\begin{aligned} f_{\lambda_{\max}}(\lambda) = {} & \left(1-e^{-\lambda}\right)e^{-\lambda}\lambda^2 - 2\left(1-e^{-\lambda}\sum_{k=0}^{1}\frac{\lambda^k}{k!}\right)e^{-\lambda}\lambda \\ & +2\left(1-e^{-\lambda}\sum_{k=0}^{2}\frac{\lambda^k}{k!}\right)e^{-\lambda} \end{aligned}. \tag{18}$$

Inserting (18) into (14), the BER is calculated and plotted in Figs. 2 and 3.

To increase the CCI tolerance of the system, we increase the number of receive antennas. Where the number of transmit antennas at each MS (both desired and cochannel users) at the fixed value 2. In this circumstance ($Tx = 2$, $Rx \geq 3$), the desired signal correlation matrix and the interference plus noise correlation matrix follow the pseudo-Wishart matrix distribution [11]. As reported in [12], it is impossible to obtain the closed form for the joint eigenvalue distribution since it involves zonal polynomial which is notoriously difficult to compute. Therefore, the efficient way for performance evaluation is resorting to Monte Carlo simulation to obtain the distribution of the beamformer output SINR, and then, calculating (14) numerically to obtain the analytical BER results.

Monte-Carlo simulation is executed to obtain the BER *vs.* SNR performance. In Fig. 2, we examine the CCI influence to the conventional Alamouti scheme without beamforming. This justifies the necessity of concatenating beamforming with the Alamouti STBC decoder in the presence of CCI. From the figure, we observe that in the presence of CCI, increasing the number of receive antennas at the receiver brings a better BER performance. However, the two curves exhibit floor as the SNR increases. The slops of the curves indicates that the in the presence of CCI, no diversity advantage is obtained from transmitting Alamouti STBC. The Alamouti STBC decoder process is a space maximum ratio combining (MRC) in nature [13, pp. 225-226], which ignores the CCI and coherently combine the signal samples according to the CSI of the desired user. It has implicit interference suppression ability but the performance is dependent on the instant CSI of both desired users and interfering users.

Figure 3, shows the performance when beamforming is combine via an increased number of receive antennas at the BS. The performance for the case when $M = 1$, $Rx = 2$ is very similar to that for the case of $M = 2$, $Rx = 4$, and their curves have the same slope. These prove that the added diversity freedom at the BS (the added receive antennas) is committed to suppressing CCI. When $M \geq 3$ with $Rx = 4$, the curves exhibit floor. In this circumstance, the BS receive antenna array has not sufficient to cope with the interference which becomes the main reason of errors as SNR → ∞. The diversity order achieved through simulation can be approximated by calculating [7, pp. 429-432]:

$$d_o = \lim_{SNR\to\infty}\left\{\frac{\log\left(P_e\left(SNR\right)\right)}{\log SNR}\right\}. \tag{19}$$

Secondly, we fix $M$ at value 2 and increase $Rx$ from 4 to 6. Results show that adding more BS receive antennas brings a better performance and a higher CCI tolerance, as we expect. From the above discussions, we conclude that suppressing one extra CCI requires two additional receive antennas at the beamformer. The technique does not require CSI of cochannel users, thus reducing the receiver computational complexity. With CSI of cochannel users, intelligent receiver algorithms such as the minimum-mean-square-error (MMSE) technique presented in [2] can be employed. The concatenation structure proposed in this paper is also applicable to further increasing the performance [14].

### *B. Achieved MIMO Channel Capacity*

In the presence of beamforming, an equivalent 2-by-1 vector channel is constructed from the MS two transmit antennas to the input at the STBC decode. Exploiting the algebraic structure of the Alamouti STBC, a 4-by-4 dimensional MIMO channel is build. Under the assumption that each CCI signal waveform is Gaussian, the theoretical Shannon is obtained for each symbol by calculating:

$$C = \log_2\left(1+\gamma^{(1)}\right)\quad \text{bits/s/Hz}. \tag{20}$$

For the full rate Alamouti scheme (two symbols are transmitted over two symbol epochs), the achieved MIMO channel capacity is expressed by (20). We observe that the beamforming process maximizes the output SINR $\gamma^{(1)}$, therefore maximizes the achieved MIMO channel capacity in the presence of CCI without CSI. The capacities for various cases studied in the previous section are shown in Fig. 4. The theoretical MIMO channel capacities are also produced according to reference [1] as benchmark for performance comparison. When $M = 1$, $Rx = 1$, it is the conventional Alamouti scheme. When $Rx = 2$, the beamforming is combined with the STBC decoder. The virtual 2-by-2 channel is constructed as in (10). The capacity is increased dramatically. In this single-user case, beamforming maximizes the SNR at the input of the STBC decoder, resulting in virtual MIMO channel with an increased SNR. When $M = 2$ and $Rx = 4$, the capacity is close to that for $M = 1$, and $Rx = 2$, so are their BER performances. When $M \geq 3$ and $Rx = 4$, the capacity drops, and the BER curves also exhibit floors (cf. Fig. 3), because of the insufficient diversity freedom to suppress CCI.

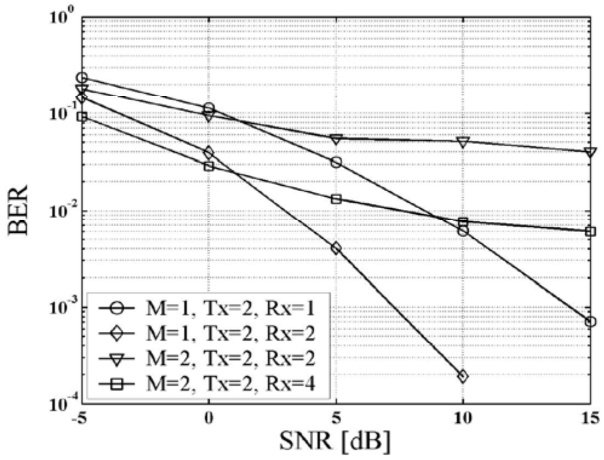

Figure 2. BER without beamforming for two conventional Alamouti schemes.

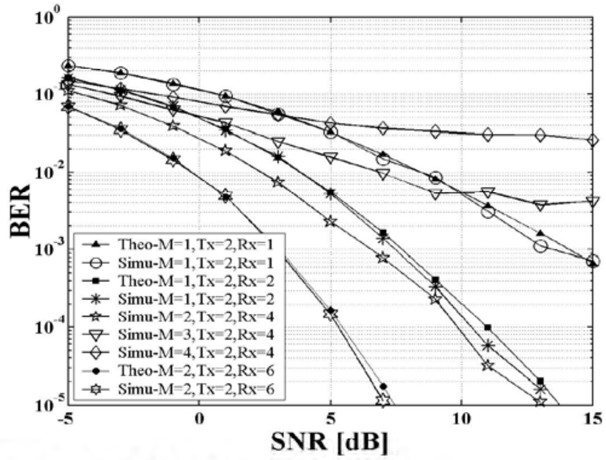

Figure 3. BER with beamforming for RX > 1.

The ergodic capacities (mean information rate) over the numbers of receive antennas for different numbers of cochannel users are produced in Fig. 5. The beamforming process increases the ergodic capacity of a conventional Alamouti scheme from 3.2 bits/s/Hz to 4 bits/s/Hz by adding one extra antenna. Comparing the three curves, it is also clear that suppressing one additional CCI while sustaining the same capacity demands two extra receive antennas.

## V. CONCLUSIONS

We have proposed a simple receiver structure that combines optimum beamforming with Alamouti STBC decoder. The technique improves the performance considerably. The receiver does not require CSI of CCI, thus keeping the computational complexity low. Through the study, the following conclusions can be drawn.

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- The output SINR is increased by virtue of the array gain, thus realizing CCI suppression.
- In the presence of the beamforming process the virtual Alamouti MIMO channel preserves the complex-orthogonal property. It is that property that allows the Alamouti STBC decoder process be achieved through simple linear processing.
- By virtue of the orthogonally, the two data streams from MS-1 two transmit antennas are completely separated at the STBC decoding stage. Therefore, CAI is suppressed.
- Extra diversity freedom is committed to suppressing CCI via the beamforming process.
- The beamforming does not require CSI of cochannel users, thus reducing the receiver computational complexity.
- When CSI of CCI is unknown, suppressing one CSI demands two extra diversity freedoms at the receiver via beamforming.

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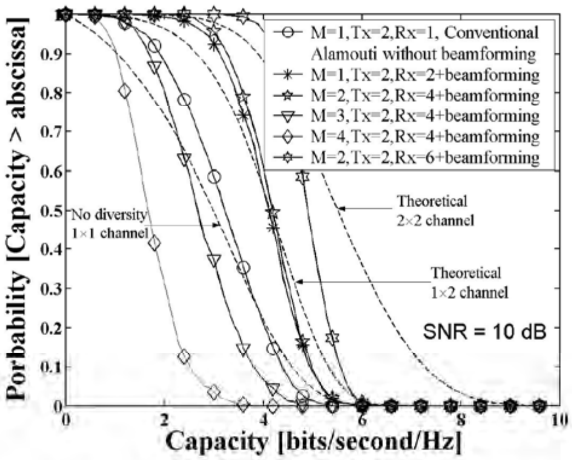

Figure 4. Channel capacities in the presence of beamforming

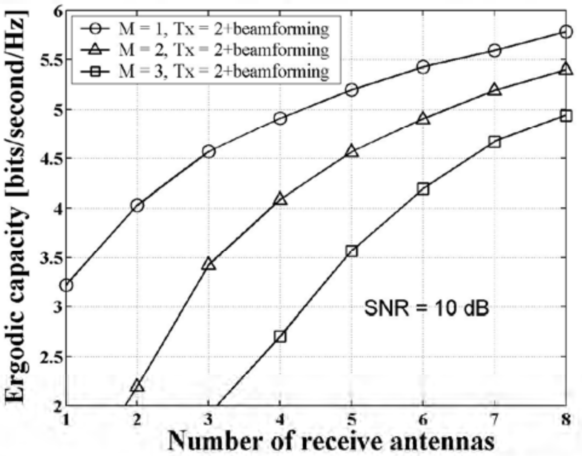

Figure 5. Ergodic capacities with beamforming over different numbers (*Rx*) of receive antennas at the BS.