Performance Analysis of Amplify and Forward Based Cooperative Diversity in MIMO Relay Channels

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***Abstract*—Tight closed form lower bounds for the average bit error rate (BER) are derived for a dual hop cooperative network employing nonregenerative relays for the multiple input multiple output (MIMO) relay channel experiencing Rayleigh fading. The bounds are obtained for three different nonregenerative relaying schemes. The lower bounds for the BER are obtained using the moment generating function (MGF) approach by evaluating the MGF of the end-to-end equivalent signal to noise ratio (SNR) of the system. From the BER expressions obtained, we also show that the diversity order for the MIMO Relay cooperative system with each relay having M antennas increases approximately by a factor M from that of a system with single-antenna relays. Simulation results confirm that the analytical expressions for the lower bounds are very tight and can thus be used to get approximate values of the BER.**

***Index Terms*—MIMO Relay, Maximal Ratio Combining (MRC), Space-Time Coding (STC), Amplify and Forward (AF)**

I. Introduction

Cooperative diversity has recently become a subject of significant interest in wireless communications as it realizes the performance of MIMO systems through multiple relays instead of having multiple transmit or receive antennas at the source and destination. Thus, instead of multiple antennas at the mobile user, antenna sharing among various users leads to improvement in the system performance.

The relays in a cooperative network may either be regenerative (decode and forward) or nonregenerative (amplify and forward). For nonregenerative relays, the amplifier gain at the relay may depend on the channel gain in the previous hop or be fixed (blind). The end-to-end SNR for a multihop amplify and forward (AF) based network with relays having single antenna was first derived in [1]. This was used to find expressions for the end-to-end BER and outage probability for systems with a single relay in [2] and for multihop relays in [3]. A comprehensive analytical treatment of the performance of dual hop cooperative networks with nonregenerative relays is available in [4]. For AF cooperative networks with multiple relays and channel state information (CSI) based gains at the relays, bounds on the performance using MRC at the destination were first provided in [5] and later improved in [6]. All this work considered a single antenna at each relay.

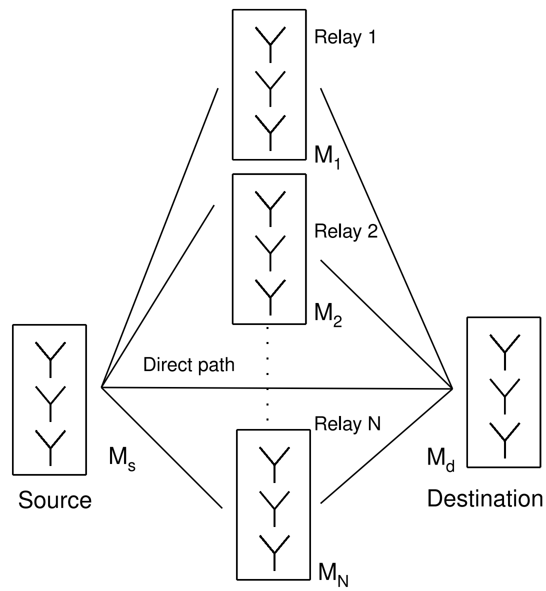

Fig. 1. Multiantenna based relay model for cooperative diversity.

In this paper, we consider an AF based cooperative system, henceforth called as MIMO relay system [7] with multiple relays where each relay supports multiple antennas. While relay diversity was introduced due to practical constraints on the number of antennas at the mobile station, the MIMO relay system is quite useful for communication across multiple base stations in large communication networks. Further, MIMO relay techniques are also feasible in the adhoc networking as the mobile station can support upto two antennas [8].

We propose an AF based diversity scheme where the same set of antennas are used at the relay to extract receive diversity on the source-relay link with MRC and transmit diversity on the relay-destination link with space-time block codes (STBC) [9], [10]. In the process, the relay combines the symbols received at the antennas and without decoding, waits for a few time slots depending on the size of the space-time code and then transmits the combined symbols using STC with CSI based gain. Tight lower bounds on the BER are obtained in closed form from the end-to-end equivalent SNR using the MGF approach. From the expressions obtained, we show that the overall diversity of the system with each relay having M antennas increases approximately by a factor M from that of a system with single-antenna relays. The simulation results and the computed lower bounds show that there is a significant coding gain in a MIMO relay system with one relay with two antennas over a system with two relays with one antenna each, though the total number of source-destination paths in both the systems are the same. We also evaluate two simpler relaying schemes. In the first, the relays do MRC and the combined signal is directly relayed through only a single antenna. In the second, the relays use the received signals from all the antennas and use them directly to construct the space-time codeword for relaying through all the antennas. Tight lower bounds on the BER are also obtained for these schemes. The degradation of performance of these schemes compared to the MRC-STC relaying scheme are assessed using these analytical bounds on the BER as well as the simulation results.

In Section II, we present the system model and three relaying schemes. In Section III, lower bounds on the BER for these three relaying schemes are derived. The diversity order of the MRC-STC relaying scheme is also derived in this section. Simulation results for the BER of these schemes along with the corresponding lower bounds are presented in Section IV. The effect of the relay position, and BER of comparable single-antenna relay systems are also discussed with simulation results. Section V concludes the paper.

II. System model

We extend the model in [11] so that, as shown in Fig. 1, the source (S), relays (R) and the destination (D) may now support multiple antennas. There are N relays in the system. The source has M_s transmit antennas, the r-th relay has M_r antennas that are used for reception on the S-R link and transmission on the R-D link, and the destination has M_d receive antennas. All transmissions are on orthogonal channels using binary phase shift keying (BPSK). We restrict ourselves to the case of $M_s = M_d = 1$ for simplicity, though the analytical results can be easily extended to more general values. Further, the transmit power E_r available at the relay is assumed to be equally distributed among all the available antennas. Let x be the symbol transmitted at the source with energy E_s. The corresponding received symbol at the i-th antenna of the r-th relay is represented by $y^i_{r,s}$. We denote the fading coefficients on the S-D, S-R and R-D links as $a_{d,s}$, $a^i_{r,s}$ and $a^i_{d,r}$ respectively. Here the first subscript indicates the receiver unit, the second subscript indicates the transmitter unit, and the superscript indicates the antenna index at the receiver unit. The corresponding additive white Gaussian noise (AWGN) samples are respectively denoted by $n_{d,s}$, $n^i_{r,s}$ and $n^i_{d,r}$. The received symbol on the $S-D$ and $D-R$ links are respectively given by

$$\begin{aligned} y_{d,s} &= \sqrt{E_s} a_{d,s} x + n_{d,s}, \quad \text{and} \\ y^i_{r,s} &= \sqrt{E_s} a^i_{r,s} x + n^i_{r,s}. \end{aligned} \tag{1}$$

The channels are assumed to be Rayleigh fading. Hence $a_{d,s} \sim \mathcal{CN}(0, \Omega_{d,s})$, $a^i_{r,s} \sim \mathcal{CN}(0, \Omega_{r,s})$ and $a^i_{d,r} \sim \mathcal{CN}(0, \Omega_{d,r})$ are circularly symmetric complex Gaussian random variables with zero mean and corresponding variances $\Omega_{\cdot,\cdot}$. Also, $n_{d,s}, n^i_{r,s}, n^i_{d,r} \sim \mathcal{CN}(0, N_0)$ with N_0 being the noise variance. The AF mechanism is then used at the relays using different combinations of MRC and STC to achieve cooperative diversity. These are discussed in the following subsections.

A. Relaying with only MRC at the Relay

Applying MRC at the r-th relay, we have

$$x_r = \sum_{i=1}^{M_r} \sqrt{E_s} a^{i*}_{r,s} y^i_{r,s}. \tag{2}$$

The symbol x_r is now transmitted by the r-th relay using a fixed single antenna. The power used for this transmission, obtained as a direct extension of [12], is given by

$$\beta_r = \sqrt{\frac{1}{C_r E_s + N_0}}, \quad C_r = \textstyle\sum_{i=1}^{M_r} |a^i_{r,s}|^2. \tag{3}$$

The signal received at the destination can be expressed as

$$y_{d,r} = \beta_r \sqrt{E_r} a_{d,r} x_r + n_{d,r}. \tag{4}$$

The maximum likelihood (ML) decision at the receiver based on the combined signal received from the relays and the signal received from the source, is given by [11]

$$\text{Re}\left\{ a^*_{d,s} y_{d,s} + \sum_{r=1}^{N} \frac{\beta_r C_r \sqrt{E_S}\sqrt{E_r}}{\beta_r^2 C_r E_s E_r |a_{d,r}|^2 + 1} a^*_{d,r} y_{d,r} \right\} \underset{-1}{\overset{1}{\gtrless}} 0. \tag{5}$$

B. Relaying with only STC at the Relay

For STC, we restrict to the case of $M_r = 2$ and use the Alamouti code [8] at each relay for transmission, though our analytical results extend to more general M_r with any orthogonal space-time code. The received symbol from the i-th antenna is subjected to the power constraint

$$\beta^i_r = \sqrt{\frac{1}{|a^i_{r,s}|^2 E_s + N_0}} \tag{6}$$

before using them to form the space-time codeword

$$\begin{pmatrix} \beta^1_r y^1_{r,s} & \beta^2_r y^2_{r,s} \\ -\beta^2_r y^{2*}_{r,s} & \beta^1_r y^{1*}_{r,s} \end{pmatrix}. \tag{7}$$

Here the rows represent the time slots and the columns represent the transmit antennas. The symbols received at the destination from the r-th relay in consecutive time slots are given by

$$\begin{aligned} y_{d,r,1} &= \sqrt{E_r}(\beta^1_r a^1_{d,r} y^1_{r,s} + \beta^2_r a^2_{d,r} y^2_{r,s}) + n_{d,r,1}, \\ y_{d,r,2} &= \sqrt{E_r}(-\beta^2_r a^1_{d,r} y^{2*}_{r,s} + \beta^1_r a^2_{d,r} y^1_{r,s}) + n_{d,r,2}. \end{aligned}$$

The symbols are combined as

$$z_r = \sqrt{E_r} a^{1*}_{d,r} y_{d,r,1} + \sqrt{E_r} a^2_{d,r} y^*_{d,r,2}. \tag{8}$$

Defining $D_r = \sum_{i=1}^{2} |a^i_{d,r}|^2$, we obtain, in the same way as in [11], the ML decision rule

$$\text{Re}\left\{ a^*_{d,s} y_{d,s} + \sum_{r=1}^{N} \frac{\beta^1_r}{(\beta^1_r)^2 D_r E_r + 1} a^{1*}_{r,s} z_r \right\} \underset{-1}{\overset{1}{\gtrless}} 0. \tag{9}$$

Note that in this scheme, ignoring the delay introduced by the AF protocol, two time slots are being used to decode only one symbol.

C. Relaying with MRC and STC at the Relay

Again, we assume $M_r = 2$ for simplicity. In this scheme, each relay combines the signals received from all the antennas. Two combined symbols obtained in two consecutive time slots are used to form one Alamouti codeword for relaying. The ML decision rule is given by

$$\text{Re}\left\{a_{d,s}^* y_{d,s} + \sum_{i=1}^{N} \frac{\beta_r C_r \sqrt{E_s}}{\beta_r^2 C_r D_r E_r E_s + 1} z_r\right\} \underset{-1}{\overset{1}{\gtrless}} 0. \quad (10)$$

Unlike the relaying scheme with only STC, the MRC-STC scheme provides full rate.

For all the schemes discussed in this section, the expression for the BER can be written as $P_e = \int_{-\infty}^{\infty} Q(\sqrt{2\gamma_{eq}})d\gamma_{eq}$, where γ_{eq} is the equivalent signal to noise ratio (SNR) for the decision variable in (5), (9) and (10). For BPSK modulation, this may be expressed [13] in terms of the MGF of γ_{eq} as

$$P_e = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} M_{\gamma_{eq}}\left(\frac{1}{\sin^2\theta}\right)d\theta. \quad (11)$$

III. BER Performance analysis

We define the gamma distribution which will be necessary for BER performance analysis for different schemes.

Definition 3.1: [14] (Gamma distribution) The probability density function (PDF) of a random variable γ with gamma distribution with mean $\overline{\gamma}$ and order m is defined as

$$p_\gamma(x) = \frac{x^{m-1}e^{-(x/\overline{\gamma})}}{\overline{\gamma}^m\Gamma(m)}. \quad (12)$$

We define the respective equivalent SNR [2] on the S-D, S-R and R-D links as $\gamma_{d,s}, \gamma_{r,s}, \gamma_{d,r}$ with $\overline{\gamma}_{d,s} = E[\gamma_{d,s}], \overline{\gamma}_{r,s} = E[\gamma_{r,s}]$ and $\overline{\gamma}_{d,r} = E[\gamma_{d,r}]$.

We derive the approximate BER expression for different relaying schemes in the following subsections.

A. BER for relaying with only MRC

From (5), using the approach in [2], we obtain

$$\gamma_{d,s} = \frac{E_s}{N_0}|a_{d,s}|^2, \gamma_{r,s} = \frac{E_s}{N_0}C_r, \gamma_{d,r} = \frac{E_r}{N_0}|a_{d,r}|^2. \quad (13)$$

The equivalent end-to-end SNR can then be expressed as

$$\begin{aligned}\gamma_{eq} &= \gamma_{d,s} + \sum_{r=1}^{N}\frac{\gamma_{r,s}^2\gamma_{d,r}}{1+\gamma_{r,s}+\gamma_{r,s}\gamma_{d,r}} \\ &< \gamma_{d,s} + \sum_{r=1}^{N}\frac{\gamma_{r,s}\gamma_{d,r}}{1+\gamma_{d,r}}. \quad (14)\end{aligned}$$

Though this is an upper bound, this gives a very close approximation for $\gamma_{r,s} >> 1$. Defining $\gamma_r = \gamma_{r,s}\gamma_{d,r}/(1+\gamma_{d,r})$, and noting that $\gamma_{d,s}, \gamma_{r,s}$ and $\gamma_{d,r}$ are all gamma distributed [15], the MGF of γ_r is obtained in (15) from [4, Eq. (27)], where $m_{d,r} = 1, m_{r,s} = M_r, \overline{\gamma}_{r,s} = M_r\Omega_{r,s}E_s/N_0$ and $\overline{\gamma}_{d,r} = \Omega_{d,r}E_r/N_0$ and $W_{\lambda,\mu}(.)$ is the Whittaker function [16]. Also from [13], we have

$$M_{\gamma_{d,s}}(s) = \frac{1}{1+s\overline{\gamma}_{d,s}}, \quad (16)$$

where $\overline{\gamma}_{d,s} = \Omega_{d,s}E_s/N_0$. Thus, from (14), (15) and (16) we obtain

$$M_{\gamma_{eq}}(s) = M_{\gamma_{d,s}(s)}\prod_{r=1}^{N}M_{\gamma_r}(s). \quad (17)$$

Substituting (17) in (11) gives a closed form expression for the BER.

B. BER for relaying with only STC

For $M_r = 2$, from (9) we obtain

$$\gamma_{d,s} = \frac{E_s}{N_0}|a_{d,s}|^2, \gamma_{r,s} = \frac{E_s}{N_0}|a_{r,s}^1|^2, \gamma_{d,r} = \frac{E_r}{N_0}D_r. \quad (18)$$

The equivalent end-to-end SNR can then be expressed as

$$\gamma_{eq} = \gamma_{d,s} + \sum_{r=1}^{N}\frac{\gamma_{r,s}\gamma_{d,r}}{1+\gamma_{r,s}+\gamma_{d,r}}. \quad (19)$$

It is obvious that $\gamma_{d,s}, \gamma_{r,s}, \gamma_{d,r}$ are all gamma distributed. Defining $\gamma_r = \gamma_{r,s}\gamma_{d,r}/\left(1+\gamma_{r,s}+\gamma_{d,r}\right)$, we obtain from [6] an approximate expression for $M_{\gamma_r}(s)$ in (21), where ${}_mF_n(.)$ is the Hypergeometric function [16]. Also, $m_{r,s} = 1$, $m_{d,r} = M_r$, $\bar{\gamma}_{r,s} = \Omega_{r,s}E_s/N_0$, and $\bar{\gamma}_{d,r} = M_r\Omega_{d,r}E_r/N_0$. From (21), (16) and (17) we obtain the expression for the equivalent MGF, and using it in (11), we get a closed form expression for the BER.

C. BER for relaying with MRC and STC

From (10), we obtain

$$\gamma_{d,s} = \frac{E_s}{N_0}|a_{d,s}|^2, \gamma_{r,s} = \frac{E_s}{N_0}C_r, \gamma_{d,r} = \frac{E_r}{N_0}D_r. \quad (22)$$

The equivalent end-to-end SNR can then be expressed as

$$\begin{aligned}\gamma_{eq} &= \gamma_{d,s} + \sum_{r=1}^{N}\frac{\gamma_{r,s}^2\gamma_{d,r}}{1+\gamma_{r,s}+\gamma_{r,s}\gamma_{d,r}} \\ &< \gamma_{d,s} + \sum_{r=1}^{N}\frac{\gamma_{r,s}\gamma_{d,r}}{1+\gamma_{d,r}} \quad (23)\end{aligned}$$

Again, this upper bound gives a very good approximation for $\gamma_{r,s} >> 1$. Using an approach similar to the one in Section III.A, an expression for the BER is obtained from (15), (16), (17) and (11) for $m_{r,s} = m_{d,r} = M_r$, $\bar{\gamma}_{r,s} = M_r\Omega_{r,s}E_s/N_0$, and $\bar{\gamma}_{d,r} = M_r\Omega_{d,r}E_r/N_0$.

D. Diversity order for MRC-STC

For $\gamma_{d,r} >> 1$ eq. (16), (17), and (23) gives

$$M_{\gamma_{eq}}(s) \approx \frac{1}{(1+s\bar{\gamma}_{d,s})(1+s\frac{\bar{\gamma}_{r,s}}{M_r})^{2N}}. \quad (24)$$

For differential phase shift keying (DPSK), the BER is given by $P_e = 0.5M_{\gamma_{eq}}(1)$ [13]. From (24), we obtain

$$P_e \approx \frac{1}{(1+\bar{\gamma}_{d,s})^{2N+1}}, \quad (25)$$

which suggests that the diversity order is $2N+1$.

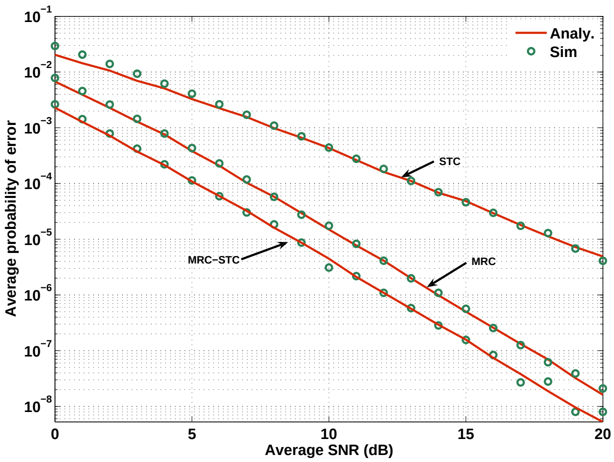

Fig. 2. Comparison of simulation and analytical results for relay located at $L = 0.5$. $M_r = 2, N = 1$.

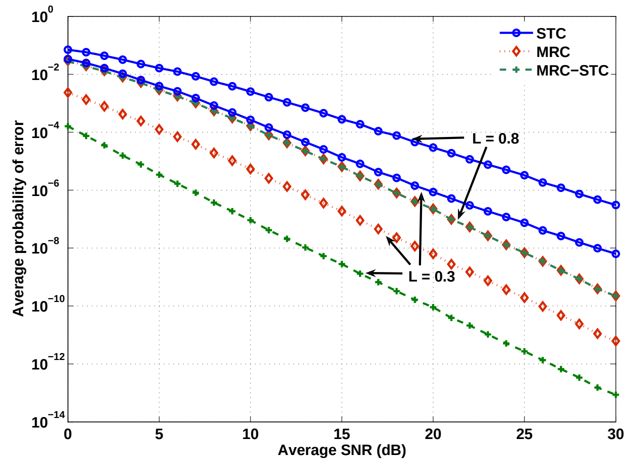

Fig. 3. Performance of MIMO relay diversity schemes for different relay locations. $L = 0.3$ and 0.8. $M_r = 2, N = 1$.

IV. Results and Discussion

The simulation parameters for our model are similar to those in [11]. The total power of one unit used by the system is assumed to be shared by the source and relays, i.e., $E_s + \sum_{r=1}^{M} E_r = 1$. Further, the relay energy E_r is shared equally among all the M_r antennas at the relay. In our simulations, we assumed $E_s = 0.5$ and the rest of the energy is equally shared by the relays. In our simulations, we have assumed that all the relays are located at the same distance from the source and also from the destination. The ratio of the distance of the relays from the source and the distance between the source and the destination is denoted by L and consequently $\Omega_{r,s} \propto 1/L^4$.

In Fig. 2, the BER of a MIMO relay system with $M_1 = 2$, $N = 1$, and $L = 0.5$ obtained from simulation and the analytical bounds are shown against average SNR at the destination. The analytical plots shown in firm lines are obtained from the BER expressions resulting from (17) and (11) for STC, MRC and MRC-STC schemes using Monte Carlo simulations. The BER values obtained by simulation are indicated by 'o'. The plots show that the simulation results follow the analytical bounds very closely.

Fig. 3 shows the BER bounds obtained from the derived analytical expressions for all the three different relaying schemes for a single relay with two antennas for $L = 0.3$ and $L = 0.8$. It should be noted that both the BER for relaying with MRC and relaying with MRC-STC for $L = 0.8$ overlap and show as a single curve in the middle. It is interesting to observe that the performance of all the schemes is much better when the relay is located closer to the source than the destination. This gives the impression that the system performance is significantly influenced by the quality of reception in the S-R link. For any L, as expected, the MRC-STC scheme performs better than the other two schemes. However, for system simplicity, the relaying with only MRC may still be of importance since it gives, for $L = 0.8$ the same BER as that of MRC-STC; and for $L = 0.3$, it only lacks by about 7 dB coding gain from MRC-STC. Since MRC efficiently utilizes the S-R links and STC utilizes the R-D links, this reinforces our observation that the S-R link is more significant in determining the system performance.

Fig. 4 shows the BER plots, computed from the analytical

$$M_{\gamma_r}(s) = 1 - \frac{s}{\Gamma(m_{d,r})} \sum_{i=0}^{m_{r,s}-1} \sum_{j=0}^{i} \binom{i}{j} \Gamma\left(m_{d,r} + i - j + 1\right) \left(\frac{m_{r,s}}{\bar{\gamma}_{r,s}}\right)^{\frac{2i+m_{d,r}-j-1}{2}} \left(\frac{m_{d,r}}{\bar{\gamma}_{d,r}}\right)^{\frac{m_{d,r}+j-1}{2}}$$
$$\cdot \left(s + \frac{m_{r,s}}{\bar{\gamma}_{r,s}}\right)^{-\frac{2i+m_{d,r}-j+1}{2}} \exp\left(\frac{m_{r,s} m_{d,r}}{2\bar{\gamma}_{d,r}\left(m_{r,s} + s\bar{\gamma}_{r,s}\right)}\right) W_{-\frac{2i+m_{d,r}-j+1}{2}, \frac{m_{d,r}-j}{2}} \left(\frac{m_{r,s} m_{d,r}}{\bar{\gamma}_{d,r}\left(m_{r,s} + s\bar{\gamma}_{r,s}\right)}\right) \quad (15)$$

$$M_{\gamma_r}(s) = \left(\frac{m_{r,s}}{\bar{\gamma}_{r,s}}\right)^{m_{r,s}} \left(\frac{m_{d,r}}{\bar{\gamma}_{d,r}}\right)^{m_{d,r}} \frac{\Gamma\left(m_{r,s} + m_{d,r}\right)}{\Gamma\left(m_{r,s}\right)\Gamma\left(m_{d,r}\right)} \frac{1}{\left(m_{d,r}/\bar{\gamma}_{d,r} + m_{r,s}/\bar{\gamma}_{d,r} + s\right)^{m_{d,r}+m_{r,s}}} \quad (21)$$
$$\cdot \left[\frac{1}{m_{r,s}} {}_2F_1\left(1, m_{r,s} + m_{d,r}; m_{r,s} + 1; \frac{m_{r,s}/\bar{\gamma}_{r,s} + s}{m_{r,s}/\bar{\gamma}_{r,s} + m_{d,r}\bar{\gamma}_{r,s} + s}\right)\right.$$
$$\left. + \frac{1}{m_{d,r}} {}_2F_1\left(1, m_{r,s} + m_{d,r}; m_{d,r} + 1; \frac{m_{d,r}/\bar{\gamma}_{d,r} + s}{m_{r,s}/\bar{\gamma}_{r,s} + m_{d,r}/\bar{\gamma}_{d,r} + s}\right)\right]$$

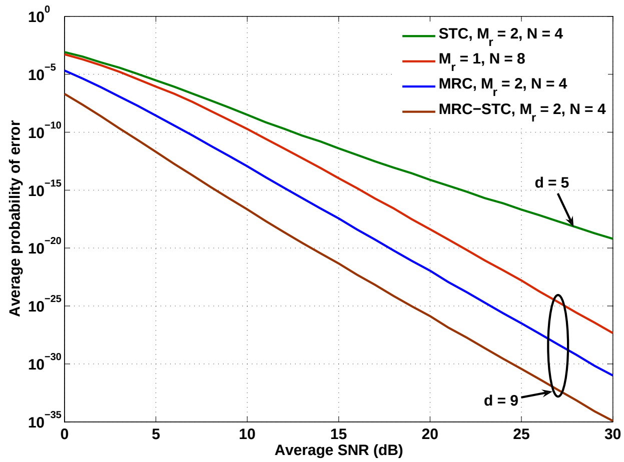

Fig. 4. Comparison of the performance of MIMO relay diversity with traditional cooperative diversity. $L = 0.5$

approximations obtained in this paper, for a MIMO relay system with $N = 4$, $M_r = 2, r = 1, \ldots, 4$ for all the three schemes. A comparable single antenna relay system with eight single antenna relays is also evaluated using approximate derivations from [6] and shown in the figure. For both the systems, we considered $L = 0.5$. The diversity order of a scheme can be computed from the BER curve since it is the asymptotic slope of the BER curve. The diversity order implied by each BER curve is indicated in the figure. The diversity order shown by the BER curve of the MRC-STC scheme is same as predicted by (25). It can be observed that the MIMO relay system with MRC-STC or MRC gives the same diversity order of nine as the single antenna relay system having the same total number of relay antennas. However, the MIMO relay system provides a significant coding gain of 9 dB over the single antenna relay system.

V. Conclusions

We have discussed the application of MRC on the S-R link and STC on the R-D link for a MIMO relay channel individually as well as jointly in the MRC-STC scheme. For BPSK modulation, we obtained decision rules for bit detection at the destination for all the proposed schemes. Using these, along with the equivalent SNR approach, expressions for the MGF of the equivalent SNR were obtained using realistic approximations which were then used to compute the BER. The validity of the approximations was verified through a comparison of results obtained from our analytical BER expressions with computer simulations. From the BER expressions obtained, we also found that the diversity order for the MIMO relay channel using AF with MRC and MRC-STC is the same as that of a single antenna multi-relay system with same number total relay antennas. This agrees with the claim made in [7] that the maximum diversity achievable in a relay system is one more than the total number of relay antennas. For the first time, this has been shown under practical transmission schemes with analytical closed form approximation of the probability of error. We also showed that the relaying scheme with only MRC at the relays achieve the same diversity order as that with both MRC and STC. So, in networks where relays with multiple antennas are available, the MRC-STC relaying scheme should be used. For system simplicity, the relaying with only MRC may also be a good option. The comparison with single antenna relay systems showed that even with a system with the same total number relay antennas, a MIMO relay system offers significant coding gain over its single antenna counterpart.

References

[1] M. O. Hasna and M. S. Alouini, “Outage probability of multihop transmission over nakagami fading channels,” *IEEE Commun. Lett.*, vol. 7, pp. 1451–1458, May 2003.

[2] M. O. Hasna and M. S. Alouini, “Harmonic mean and end-to-end performance of transmission systems with relays,” *IEEE Trans. Commun.*, vol. 52, pp. 1451–1458, January 2004.

[3] G. K. Karagiannidis, T. A. Tsiftsis, and R. K. Mallik, “Bounds for multihop relayed communications in nakagami-m fading,” *IEEE Trans. Commun.*, vol. 54, January 2006.

[4] T. A. Tsiftsis, G. K. Karagiannidis, P. T. Mathiopoulos, and S. A. Kotsopoulos, “Nonregenerative dual-hop cooperative links with selection diversity,” *EURASIP, J. Wireless Commun. Networking, article ID 17862*, vol. 2006, pp. 1–8.

[5] T. A. Tsiftsis, G. K. Karagiannidis, S. A. Kotsopoulos, and F. N. Pavlidou, “Ber analysis of collaborative dual-hop wireless transmissions,” *IEE Electronic Lett.*, vol. 40, no. 11, 2004.

[6] S. Ikki and M. H. Ahmed, “Performance analysis of cooperative diversity wireless networks over nakagami-m fading channel,” *IEEE Commun. Lett.*, vol. 11, pp. 334–336, April 2007.

[7] Y. Jing and B. Hassibi, “Cooperative diversity in wireless relay networks with multiple-antenna nodes,” in *Proceedings of IEEE International Symposium on Information Theory*, (Adelaid, Australia), pp. 815–819, September 2005.

[8] S. M. Alamouti, “A simple transmitter diversity scheme for wireless communications,” vol. 16, pp. 1451–1458, October 1998.

[9] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Trans. Inform. Theory*, vol. 45, pp. 1456–1467, July 1999.

[10] G. V. V. Sharma, V. Ganwani, U. B. Desai, and S. N. Merchant, “Maximum likelihood detection for cooperative diversity in mimo relay channels,” in *Proceedings of IEEE 65th Vehicular Technology Conference (VTC), Fall*, (Calgary, Canada), September 2008.

[11] D. Chen and J. N. Laneman, “Modulation and demodulation for cooperative diversity in wireless systems,” *IEEE Trans. Wireless Commun.*, vol. 5, pp. 1785–1794, July 2006.

[12] J. N. Laneman and G. W. Wornell, “Energy-efficient antenna sharing and relaying for wireless networks,” *IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 1, pp. 7–12, 2000.

[13] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*. John Wiley and Sons, second ed., 2005.

[14] W. Feller, *An introduction to Probability Theory and Its Applications, Vol II*. John Wiley and Sons, second ed., 1970.

[15] J. G. Proakis, *Digital Communications*. McGraw-Hill, third ed., 1995.

[16] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*. Academic Press, fifth ed., 1994.