A NEW COOPERATIVE TECHNIQUE FOR WIRELESS COMMUNICATIONS WITH IMPROVED DIVERSITY-MULTIPLEXING TRADEOFF

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ABSTRACT

In this work we present a new diversity-multiplexing scheme for the uplink transmission of a cooperative system consisting of single-antenna source and relay nodes and a multi-antenna destination node. The proposed technique is based on the singular value decomposition of the channel matrix and, for the same rate, it exhibits higher diversity gain as compared to the existing schemes. Moreover compared with these techniques it is highly reconfigurable and has a lower complexity receiver structure. We evaluate the performance of the new technique via theoretical analysis and simulations.

1. INTRODUCTION

A popular way to cope with the fading phenomena appearing in wireless communications and increase capacity is to use multiple-input, multiple-output (MIMO) systems. A MIMO system employs multiple antennas at the receiver and transmitter ends and achieves better performance than the single-input, single-output (SISO) one with the same power and bandwidth requirements. The antennas in a MIMO system can be exploited in different ways, thus offering a better performance in terms of the probability of error (diversity gain) or/and an increase in system's throughput (multiplexing gain) compared with the SISO one. During the past years, various transmission schemes have been proposed for MIMO systems that achieve different diversity and/or multiplexing gains. The so-called Diversity-Multiplexing Tradeoff (DMT) can be analyzed and quantified as proposed in [2].

However the MIMO systems suffer from some implementation related drawbacks. The major problem is the large space that multiple antennas need in order to provide maximum performance. That is, the antennas must be placed sufficiently apart to ensure that the multiple channels between the transmitter and the receiver undergo independent fading. For a base station this could not be a major problem but for the users' devices in a modern cellular network it is rather infeasible to have this distance between the antenna elements.

Cooperative communications [3] have emerged, over the past few years, as a possible means to overcome the implementation problems of MIMO systems. The main concept is to establish cooperation between single-antenna wireless systems in order to achieve some of the benefits of MIMO systems. In a generic scenario, the transmitter (source) transmits its data to adjacent nodes (relays) and then the relays forward the data to the receiver (destination). Thus, cooperation provides independent fading paths via which the data are transmitted to the receiver. Most of the cooperative schemes already presented in literature aim to achieve the highest possible diversity gain. Very few works study how multiplexing gain can be extracted from a cooperative system. Note however, that the meaning of multiplexing gain in a cooperative system is quite different from the one in MIMO systems. In a half-duplex cooperative system, the transmission of a symbol needs double the time compared with a typical MIMO system, since relays need extra time slots to receive the data from the source prior forwarding them to the destination. Thus, diversity gain comes at a cost of bandwidth efficiency, since cooperative systems have half the rate of the SISO ones. So far, the schemes already proposed try to solve this problem and increase the attainable rate.

Two different approaches have already been presented in the aforementioned direction. In the first one, slotted cooperation protocols [4] are used offering a better DMT than the generic ones at the expense of noise interference caused by the simultaneous transmissions of the nodes. In the second approach [5] - [6], the receiver has multiple antennas. The idea is to transmit a high rate data stream from the source to the relays which, in turn, transmit simultaneously the received data with a reduced rate to the destination. According to this approach a new symbol is transmitted every $N/(N+1)$ time slots (for a N-relay system) whereas in the early cooperative schemes the rate is 1/2 [3]. The first approach attains the same rate (i.e., $N/(N+1)$) but now N is the number of slots used by the scheme. Thus, with the second approach we don't have interference but the system performance depends on the number of relays and the number of destination's antennas. If any of the above numbers is reduced, the system performance is decreased as well. Moreover, in the second approach the direct transmission path from the source to the destination is ignored and a V-BLAST decoding scheme is used at the receiver which has inferior performance in terms of diversity gain.

Motivated by the second approach which fits perfectly to an uplink transmission scenario of a cellular network, we developed a new technique based on Singular Value Decomposition (SVD) beamforming which has been a well-studied approach in MIMO systems [7]. This technique exploits the properties of channel matrix SVD to create multiple independent channels (singular channels) through which the symbols are transmitted simultaneously to the transmitter. This technique turns out to achieve superior performance in terms of probability of error as compared to existing transmission schemes.

The new technique achieves better DMT than the ones of [5]-[6], offering at the same time a lower complexity re-

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ceiver structure. Moreover it is highly reconfigurable, that is, the system can very easily adjust its transmission rate according to the requirements of the corresponding application. A drawback of the new technique is that channel state information (CSI) (i.e., the right singular vectors of the channel matrix) is required at the transmission nodes. Note that the schemes proposed in [5] - [6] need CSI only at the receiver. As discussed in Section 2 the rate of the feedback channel can be drastically reduced by employing appropriate techniques for modeling the right singular vectors. In Section 2 we describe the proposed technique for the Decode and Forward (DF) and the (Amplify and Forward) AF cooperation protocols, in Section 3 we present the performance analysis concerning the DMT for the DF protocol and in Section 4 we present some representative simulation results. Finally, Section 5 concludes the work.

2. SYSTEM DESCRIPTION

Let us consider a system with a single-antenna source and a multi-antenna base station (destination), and let us also assume that other single-antenna users are available and willing to participate in a cooperative transmission scenario. A system with N relays and $M \geq N$ antennas at the receiver is depicted in Figure 1.

In the beginning we will describe the system for the case of the DF cooperation protocol. The time frame is divided into two periods. During time period T1 (Table 1) the source transmits L consecutive symbols $x(n), 1 \leq n \leq L \in [1,N]$ to the relays and the received samples at the destination and the relay nodes are given as

$$\mathbf{y}_D(n) = \mathbf{h}_{SD} x(n) + \mathbf{w}(n) \tag{1}$$

$$y_{R_i}(n) = h_{SR_i} x(n) + w_i(n), \quad 1 \leq i \leq N \tag{2}$$

where $\mathbf{y}_D(n) = [y_{D_1}(n) \ \cdots \ y_{D_M}(n)]^T$ is the received vector, $\mathbf{h}_{SD} = [h_{SD_1} \ \cdots \ h_{SD_M}]^T$ contains the taps of the channel between the source and the destination antennas, $h_{SR_i}(n)$ is the tap of the channel between the source and the i-th relay, $x(n)$ is the transmitted symbol, $\mathbf{w}(n) \in \mathscr{C}^{M\times 1}$and $w_i(n) \in \mathscr{C}$ are complex noise circular symmetric variables. We assume that the channel undergoes Rayleigh block fading, thus it changes every L+1 time symbols. The relay nodes detect the symbols based on the received signals described by (2), and subsequently, at the L+1 time slot (period T2 in Table 1), they forward simultaneously the correctly detected data to the destination. As depicted in Figure 1, the data that each relay forwards is a superposition of the L' symbols detected correctly. For the i-th relay the weights in the superposition are the first L' elements of the i-th row of the right singular vectors' matrix $\mathbf{V}_{1:N,1:L'}$. Matrix $\mathbf{V}_{1:N,1:L'}$ is computed by the singular value decomposition of the virtual MIMO channel matrix $\mathbf{H}_{RD}$

$$\mathbf{H}_{RD} = \begin{bmatrix} h_{R_1D_1} & \cdots & h_{R_ND_1} \\ \vdots & \ddots & \vdots \\ h_{R_1D_M} & \cdots & h_{R_ND_M} \end{bmatrix}, \tag{3}$$

where $h_{R_iD_j}$ is the tap of the channel between the i-th relay and the j-th destination antenna. Thus, during the T2 transmission period the received samples at the destination node are

$$\mathbf{y}_D(L+1) = \mathbf{H}_{RD}\mathbf{x}'(L+1) + \mathbf{w}(L+1), \tag{4}$$

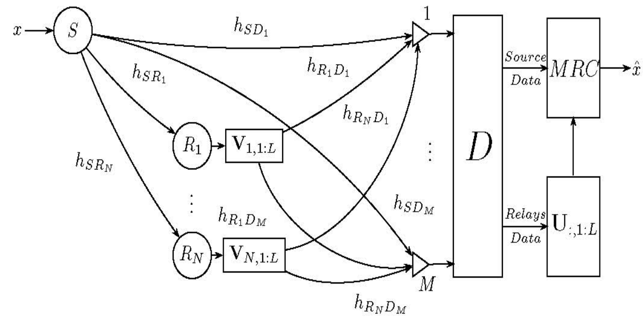

Figure 1: The proposed system.

S->R,S->D	R->D
T1	T2

Table 1:Medium access control.

where $\mathbf{x}'(L+1) = \mathbf{V}_{1:N,1:L'}\mathbf{x}(L+1)$, $\mathbf{H}_{RD} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$, $\mathbf{x}(L+1) = [\hat{x}(1), \cdots, \hat{x}(L')]^T$ is the vector with the subset of the correctly detected symbols and $\mathbf{w}(L+1) \in \mathscr{C}^{M\times 1}$. The received vector at the destination is post-coded with the corresponding left singular vector sub-matrix $\mathbf{U}_{1:M,:1:L'}$, resulting in

$$\begin{aligned} \mathbf{y}'_D &= \mathbf{U}^H_{1:M,:1:L'}\mathbf{y}_D(L+1) \\ &= \mathbf{U}^H_{1:M,:1:L'}\left\{\mathbf{H}_{RD}\mathbf{V}_{1:N,1:L'}\mathbf{x}(L+1) + \mathbf{w}_2(L+1)\right\} \\ &= \mathbf{\Sigma}\mathbf{x}(L+1) + \mathbf{w}'(L+1), \end{aligned} \tag{5}$$

where $\mathbf{\Sigma}$ is a diagonal matrix containing the singular values of the decomposition and $\mathbf{w}'(L+1) \in \mathscr{C}^{L'\times 1}$ due to the unitary property of singular vectors. Thus, we have an equivalent system in which the L' symbols are transmitted via the respective independent parallel singular channels. Note that the i-th channel tap is equal to the i-th singular value.

Since the singular values are independent of the h_{SD_i} channel taps we can use a combination of (1) and (5) to extract higher diversity gain. More precisely, for each symbol that was detected correctly from the relays we have M transmission paths from (1) and one path from (5). The latter path is the corresponding singular channel and it contributes implicitly to the overall diversity gain. The diversity gain for each symbol depends on the singular channel via which it was transmitted. According to [7] the performance of a MIMO system is dominated by the performance of the singular channel with the smallest singular value. Based on [7] we can deduce that the diversity gain of the relay-destination branch of the system (virtual MIMO) is $(N-L'+1)(M-L'+1)$. In the proposed system, as we have already mentioned, we have additionally the M direct paths between the source and the destination. Thus, as shown in the Appendix, if all the L symbols are detected correctly at the relays, we can achieve a diversity gain of $(N-L+1)(M-L+1)+M$ employing Maximum Ratio Combining (MRC) on the equivalent SIMO system

$$\mathbf{y}^i_D = \mathbf{h}^i_{eq}\mathbf{x}_i + \mathbf{w}_i, \quad 1 \leq i \leq L \tag{6}$$

where $\mathbf{y}_D^i = \left[\mathbf{y}_D^T(i), {y'}_D^i(L+1)\right]^T$, ${y'}_D^i(L+1)$ is the i-th element of $\mathbf{y'}_D$, $\mathbf{h}_{eq}^i = \left[\mathbf{h}_{SD}^T, \sigma_i\right]^T$, σ_i is the i-th singular value, $\mathbf{w}_i = \left[\mathbf{w}^T(i), w'_i(L+1)\right]^T$ and $w'_i(L+1)$ is the i-th element of $\mathbf{w}'(L+1)$.

We should note that if a symbol is not correctly detected in one of the relays it will not be forwarded by any of the relays. This is because, if one or more relays forward erroneous symbols, matrix $\mathbf{\Sigma}$ of equation (5) will no longer be diagonal and hence the system will have inferior performance. Thus, the specific symbol that is not forwarded by the relays can only be detected through the M direct transmission paths (again with the use of MRC). As it will be shown in the following section, we can avoid this problem by employing specific strategies, so that the proposed system finally achieves the already mentioned diversity.

In the AF protocol case the system is less complicated, thus the received symbols at the relays are simply multiplied with an amplification factor given in [3] and they are precoded with the same way as in the DF case. The only difference with the DF case is that the precoding and decoding matrices are computed now by the SVD of the following overall source-relay-destination channel matrix $\mathbf{H}_{SRD}$

$$\mathbf{H}_{SRD} = \begin{bmatrix} h_{R_1D_1}\beta_1 h_{SR_1} & \cdots & h_{R_ND_1}\beta_N h_{SR_N} \\ \vdots & \ddots & \vdots \\ h_{R_1D_M}\beta_1 h_{SR_1} & \cdots & h_{R_ND_M}\beta_N h_{SR_N} \end{bmatrix}. \quad (7)$$

During T1 period the system is described also by (1) and (2). The equations describing the system during T2 period are

$$\mathbf{y}_D(L+1) = \mathbf{H}_{RD} \odot \mathbf{X}' + \mathbf{w}(L+1), \mathbf{X}' = \mathbf{V}_{1:N,1:L}\mathbf{X},$$

$$\mathbf{X} = \begin{bmatrix} \beta_1 y_{R_1}(1) & \cdots & \beta_N y_{R_N}(1) \\ \vdots & \ddots & \vdots \\ \beta_1 y_{R_1}(L) & \cdots & \beta_N y_{R_N}(L) \end{bmatrix}, \quad (8)$$

where with $\mathbf{A} \odot \mathbf{B}$ we denote the dot operation between the i-th row of $\mathbf{A}$ and the i-th column of $\mathbf{B}$ for $1 \le i \le N$,$\mathbf{H}_{RD}$ is given by (3) and the value of β_i is specified as in [3] . The received vector at the destination is post-coded with the equivalent left singular vectors' sub-matrix $\mathbf{U}_{1:M,:1:L}$, thus again the system is described by equation (5) and now we can employ, in a similar manner to the DF case, the MRC method so as to detect the received symbols at the destination.

Before closing this section let us see how transmission nodes acquire the required elements of the singular vectors' matrix, so as to precode the symbols to be transmitted. A common approach, is based on a low-rate feedback channel via which the corresponding elements will be transmitted from the destination to the transmission nodes. The feedback rate is dictated by channels' coherence time. If channels vary too fast we can employ simple prediction mechanisms to the transmission nodes in order to reduce the feedback rate [8]. Note that each one of the transmission nodes must know only a specific row of the singular vectors' matrix. Thus, it needs to track only the taps of the predictor corresponding to this row, preserving the low complexity of the proposed scheme .

3. PERFORMANCE ANALYSIS

In this section we present a performance analysis of the proposed scheme for the DF cooperation protocol. A similar analysis for the AF case is under study. Let us assume that we have a system with N relays and M receive antennas and we send L symbols per block transmission. The channels undergo Rayleigh block flat fading (of length L+1). If no detection errors occur at the relays the DMT of the system is given by Theorem 1.

Theorem 1: The DMT curve of the proposed scheme under the DF protocol and the assumption that no detection errors occur at the relays is,

$$d_A(r) = ((M-L+1)(N-L+1)+M)(1-r(L+1)/L) \quad (9)$$

Proof. The proof is given in the Appendix. □

Let as now compare the DMT of the new technique with the one of [6] which also employs the DF protocol. The latter technique has the same multiplexing gain $L/(L+1)$ but a very lower diversity gain compared to the proposed one. This is due to the V-BLAST like decoder employed at the receiver. Indeed, using [2] it can be shown that the DMT curve of the technique proposed in [6], under the assumption that no detection errors occur at the relays is

$$d_B(r) = (N-1)(1-r(N+1)/N) \quad (10)$$

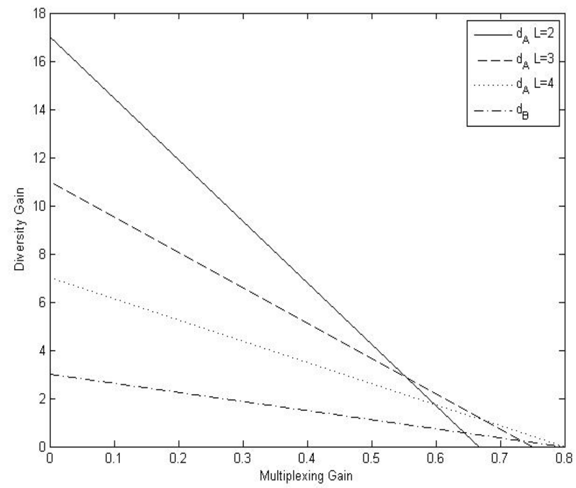

Figure 2: Comparison of the DMT of the proposed scheme with the one of [6].

The two techniques are compared in Figure 2, in terms of DMT, for various numbers of relays and destination antennas. Note that the new technique achieves better DMT performance compared to the class of the slotted protocols [4] as well. A detailed comparison with the methods in [4] is however meaningless, since the fundamental structure and functionality of these systems are completely different to the proposed one. We can also see that increasing the block length L results in $(L/(L+1)) \to 1$, which implies that the proposed cooperative system is close to optimal in terms of bandwidth utilization.

Let as now study the case that a detection error occurs in one or more relays. If a detection error occurs in one relay for one symbol, we cannot forward this symbol even though the other relays have detected it correctly, as we have already explained in Section 2. In this case, the system performance is dominated by the diversity corresponding to the symbol

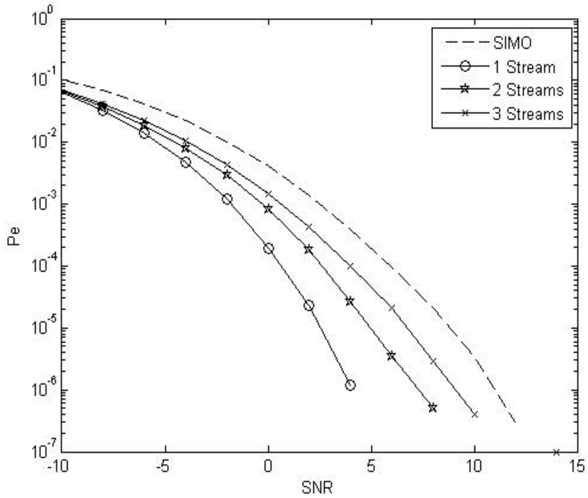

Figure 3: Performance of the new technique under the DF protocol.

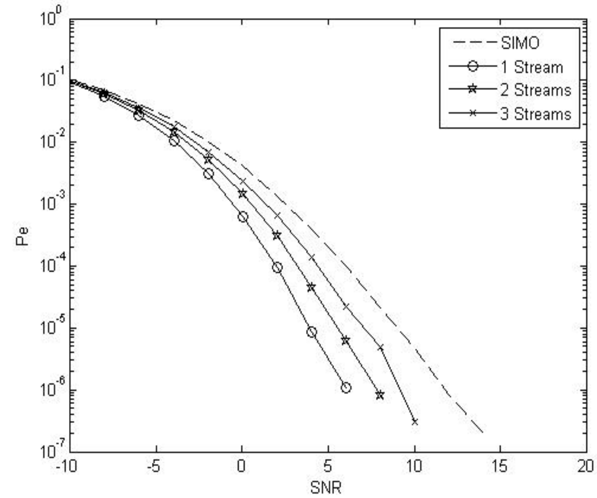

Figure 4: Performance of the new technique under the AF protocol.

which has not been relayed. So, we can extract diversity gain only through the source-destination path (M receive antennas). This may result in a major degradation in system performance, however, as we will see, there are several means to tackle this problem.

The probability of a detection error in a SISO channel is $P_e^{SISO} \approx (4SNR)^{-1}$ [1]. Thus, the probability that a detection error occurs in at least one of the relays is

$$P_f = 1 - (1 - P_e^{SISO})^N. \quad (11)$$

For a small number of relays and in high SNR environments, this probability is very small and detection errors are occurring quite rarely, and they do not affect the performance of the system. Thus, it is reasonable to assume that the proposed system achieves full diversity order in that case. The above statement is verified in the simulations section. In the case of a system with a large number of relays we can employ a relay selection scheme. Relay selection schemes can improve significantly the performance of the system since they can avoid transmissions through ill-conditioned channels. Here, we propose a simpler method that could be applicable to other similar cases as well. Let us consider a configuration with N relays. We can decrease P_f by simply transmitting the source's data to a set of $N+K \geq N$ relays. In this case, the system will suffer degradation in performance if at least $K+1$ relays fail to correctly detect one symbol. Probability P_f becomes

$$P_f \approx 1 - \left(\begin{array}{c} N+K \\ N \end{array} \right) (1 - P_e^{SISO})^N. \quad (12)$$

Thus, as expected, the availability of additional relay nodes can help the system avoid the problems caused by a non-negligible P_f at the relays.

4. SIMULATIONS

To test the performance of the proposed technique we carried out some typical experiments. The taps of all channels were generated as i.i.d. complex Gaussian variables $\mathscr{C}N(0,1)$, BPSK modulation was used and the system consisted of a single-antenna source, 3 single-antenna relays and a destination with 4 antennas. We tested the proposed technique for the AF and DF cases. In Figure 3 we present the case of DF and in Figure 4 the case of AF for block transmission lengths $L = 1,2$ and 3, respectively. In the same figure we present the case of a non-cooperation scenario as well where we extract diversity gain only through the multiple receive antennas (M). As expected, for a fixed number of relays an increase in rate results in a loss of diversity. Moreover, the DF case achieves a better performance compared to the AF, at the expense of higher implementation complexity.

5. CONCLUSION

A new diversity-multiplexing scheme for the uplink transmission of a cooperative system consisted of single-antenna source and relay nodes and a multi-antenna destination was proposed. The new technique outperforms the existing schemes since it offers a higher diversity order at the same rate. The performance of the new technique was justified theoretically and was tested via simulations.

APPENDIX

A. Preliminaries

*Definition 1:*The probability of outage of a $1 \times M$ SIMO system for a given rate R can be computed as [1]

$$P_{out}(R) = P\left\{\log\left(1 + \|\mathbf{h}\|^2 SNR\right) < R\right\}, \quad (13)$$

where $\mathbf{h} = [\ h_1 \quad \cdots \quad h_N\ ]$ is the vector with the channel gains.

Definition 2: The spatial multiplexing gain r and diversity gain d of a system are [2]

$$\lim_{SNR\to\infty} \frac{R(SNR)}{\log(SNR)} = r$$

and

$$\lim_{SNR\to\infty} \frac{\log P_e(SNR)}{\log(SNR)} = -d. \quad (14)$$

Lemma 1: For a MIMO system let the data rate scale as $R = r\log(SNR)\ \ b/s/Hz$. Then for any coding scheme the probability of error is lower-bounded by [2]

$$P_e(SNR) \geq P_{out}(r\log(SNR)). \tag{15}$$

Proof of Theorem 1: According to [7] the performance of a MIMO system employing the L - multiple beamforming scheme is dominated by the weakest singular channel (i.e., the one corresponding to the L-th smallest singular value). It is easy to verify that the performance of the scheme presented in this work is also dominated by the weakest singular channel. Thus, it is meaningful to study the performance of the part of the system that uses this channel. Such a MIMO system achieves multiplexing gain equal to L. Recall that the proposed cooperative scheme exhibits a multiplexing gain equal to is $L/(L+1)$.

In the beginning we compute the probability of outage for the overall system whose channel gains are the elements of the vector $\mathbf{h} = [\ h_1 \ \ \cdots \ \ h_N \ \ \sigma_L\ ]$. The probability of outage is computed for the scaled rate $R = r(L+1)log(SNR)/L$. From its definition we see that in order to compute the probability of outage we need to know the pdf of the random variable $\gamma = \|\mathbf{h}\|^2 = \sum_{n=1}^{N} |h_n|^2 + \sigma_L^2$. The variables $\gamma_n = |h_n|^2$ are exponentially distributed, thus their pdf is $p(\gamma_n) = e^{-\gamma_n}$. For the distribution of $\lambda_L = \sigma_L^2$, we can only obtain an approximation of its pdf around zero since an explicit expression for an arbitrary number of antennas at the receiver and the transmitter does not exist. According to [7] an approximation of the pdf of the L-th largest eigenvalue around zero is $p(\lambda_L) = \beta\lambda_L^{(M-L+1)(N-L+1)-1}$, where β is a constant. As we can see, this approximation is sufficient for the purposes of our analysis.

Random variable γ is a sum of independed random variables, thus its pdf is the convolution of their pdfs. It can be shown that the pdf of γ can be approximated as

$$p(\gamma) = \eta\gamma^{(M-L+1)(N-L+1)+M-1}, \tag{16}$$

where η is a constant. We can now compute the probability of outage with direct integration of (16) as

$$P_{out}(R) = \eta\left(\frac{2^R-1}{SNR}\right)^{((M-L+1)(N-L+1)+M)(1-r(L+1)/L)}. \tag{17}$$

So, using (13) and (14) we obtain a lower bound for the diversity gain which equals to $((M-L+1)(N-L+1)+M)(1-r(L+1)/L)$.

The next step is to compute an upper bound for the DMT. This can be done by computing the pairwise error probability (PEP). For a SIMO system the probability to decide $\hat{x}$ instead of x $(x \to \hat{x})$, for a specific instance of γ, is upper bounded from [1]

$$P(x \to \hat{x}|\gamma) \leq Q\left(\sqrt{\frac{SNR\|\gamma\|^2 d_{\min}^2}{2}}\right), \tag{18}$$

where $d_{\min}$ is the minimum Euclidean distance in the used constellation and Q is the well known $Q-$function. To simplify the analysis we will use a common upper bound for the $Q-$function, i.e., $Q(x) \leq \left(1/2\right)e^{-x^2/2}$. From the above it is clear that an upper bound for PEP can be computed as

$$P(x \to \hat{x}) \leq \int_0^\infty P(x \to \hat{x}|\gamma)\,p(\gamma)\,d\gamma, \tag{19}$$

Direct integration of (19) is a very difficult task so will we try to simplify the integral in order to derive a useful expression for PEP. First, the exponential term tends to zero as γ tends to infinite. So we can evaluate PEP around zero to gain insight to the diversity of the system. Thus, it is very easy to see that in such a case PEP is bounded from

$$P(x \to \hat{x}) \leq \eta\left(\frac{d_{\min}^2}{SNR}\right)^{(M-L+1)(N-L+1)+M}, \tag{20}$$

where in η we have incorporated any other multiplicative factor. We can assume the use of a quadrature amplitude modulation (QAM) constellation. For each symbol we choose the distance between grid points to be $SNR^{-r(L+1)/2L}$ so as to have a constellation of size $SNR^{r(L+1)/L}, r < 1$. Thus, from the aforementioned and equation (20) we can deduce that an upper bound for the diversity gain is $((M-L+1)(N-L+1)+M)(1-r(L+1)/L)$. From the above analysis it is clear that the the DMT curve of the proposed scheme is

$$d(r) = ((M-L+1)(N-L+1)+M)(1-r(L+1)/L). \tag{21}$$

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