A Cooperative Uplink Transmission Technique With Improved Diversity–Multiplexing Tradeoff

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A Cooperative Uplink Transmission Technique with Improved Diversity-Multiplexing Tradeoff

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***Abstract*—In this paper a new Decode-and-Forward (DF) cooperative scheme is presented for half duplex uplink transmission. The technique is based on a virtual MIMO structure formed by the single antenna source and relays nodes along with a multi-antenna destination node. The new technique aims at providing increased diversity and multiplexing gains, contrariwise to existing approaches in which increased diversity gain is achieved at the cost of severe multiplexing gain loss. Furthermore the proposed scheme is extended, in a doubly opportunistic manner by incorporating both multi-user diversity and relay selection diversity. Novel criteria are suggested for selecting the best transmitting user and/or the best relays at each time slot. The theoretical outage probability and the corresponding Diversity Multiplexing Trade-off (DMT) curve of both the proposed technique and its opportunistic extension are derived. Indicative simulations verify the theoretical results and compare the performance of the proposed technique to the one of existing cooperative schemes and to the one of the non cooperative SIMO system.**

***Index Terms*—Cooperative Communications, Relays, Virtual MIMO, Diversity-Multiplexing Tradeoff, Decode-and-Forward (DF), Outage Probability, Parallel Channel Decomposition**

I. INTRODUCTION

A common way to combat the fading effects that degrade the performance of wireless transmissions is the use of multiple-antenna systems so as to achieve spatial diversity [1]. However, in many cases, the nature of the communication devices does not permit the support of multiple antennas due to size, power consumption, and hardware limitations [2]. To this end, cooperative communications [3] provide an alternative way to achieve spatial diversity via virtual antenna arrays formed by single antenna nodes.

During the past years, a number of different techniques that achieve diversity via node cooperation were proposed in literature (see [4]-[8] and references therein). The majority of them aim to develop techniques that provide cooperative diversity in half duplex nodes at the expense of multiplexing gain. In fact, the transmissions exhibit severe multiplexing gain loss since a transmission from the source to the destination node requires two orthogonal channels (source to relay(s) and relays(s) to destination) that in general are created via a typical time division approach [4].

To this end, a number of different approaches have already been suggested in order to improve the multiplexing gain of the resulting cooperative techniques.

In [9]-[11], cooperative schemes have been proposed in which the source to relay(s) and the relays(s) to destination channels are non-orthogonal. The resulting techniques exhibit a better DMT than the initial cooperative schemes [4] at the expense of noise interference caused by the simultaneous transmissions of the nodes.

In [12]-[13] a superposition coding approach was proposed where the multiplexing gain is improved by permitting each user to transmit a linear combination of its own information and other users' information. At the destination node, the superposition decoder extracts multiple modulated symbols by using log-likelihood ratios which requires precise knowledge of the instantaneous fading gains, the noise variance and the linear combination coefficients that the superposition codeword employs. Therefore, an imperfect knowledge of the combination coefficients leads to severe performance degradation. Moreover, a method that provides an efficient design for the latter coefficients is in general unknown.

Incremental relaying [4],[14] can also be employed so as to improve spectral efficiency. In this approach, the relay nodes provide assistance only if the direct source to destination link fails to support the data rate. Nevertheless, an obvious disadvantage is that the incremental relaying based techniques cannot be applied in regimes where direct source to destination path does not exist (which is a very common case in the cooperative systems' literature).

The network coded cooperation [15]-[17] and two-way relaying [18]-[20] approaches can also be considered as solutions which provide improved multiplexing gains by combining the benefits of relaying and network coding. In these approaches, the relays forward a reversible function of the data (the simplest approach is based on the exclusive OR, i.e. XOR) of multiple users in one timeslot so as to increase spectral efficiency. The destination node(s) are able to decode the data provided that a source-destination direct link exists or a two-way communication approach between pairs of network nodes can be assumed. Depending on the technique implemented, the multiplexing gain can be dependent on the number of the available users and can come at a cost in diversity gain and/or of interference corrupted transmissions due to loss of orthogonality.

An interesting approach is also presented in [21] where the multiplexing gain of orthogonal relay protocols can be improved by employing rotated n-dimensional constellations. The technique improves the multiplexing gain of orthogonal protocols from 1/2 to $n/(n+1)$ for a single relay and to $n/(n+N)$ for N relays while achieving the maximum diversity gain (2 and $N+1$ respectively). As it is evident, the decoding complexity at the destination can be increased significantly since constellations of high dimension are required in order to improve significantly the multiplexing gain, especially when the number of relays is large.

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Another approach was presented in a series of papers under the term of Cooperative Spatial Multiplexing (CSM) [22]-[27]. In this approach, the source transmits in consecutive timeslots N symbols to N relays. Then, the $n-th$ relay tries to decode (or amplifies- depending on the relaying strategy) only the $n-th$ symbol. Finally, at $N+1$ timeslot, the relays that have successfully decoded the corresponding symbols forward simultaneously the decoded symbols to the multi-antenna destination (or simply forward the corresponding received signals scaled by the amplification factor). The CSM approach achieves increased multiplexing gain compared to the traditional relaying techniques, though it suffers from severe diversity gain loss, especially when the Decode-and-Forward (DF) protocol is employed. Moreover, it is not possible to exploit a direct transmission path between the source and the destination nodes (provided that there is one) so as to achieve higher diversity gains.

In [28] a multi-antenna base station is assumed that employs a cooperative scheme during the downlink communication. At first, the base station (source node) transmits symbols to the targeted users (destination nodes) and their corresponding relays in consecutive orthogonal timeslots. Then in a common timeslot all the relays forward simultaneously the data to the destination nodes. The latter approach achieves increased multiplexing gain, however, the received data at the destinations are corrupted by interference that is generated due to the relays' simultaneous transmissions.

In typical wireless systems (i.e. cellular networks), the mobile users are communicating via base stations that are deployed in specific areas. The base stations can in general be complex systems with large multi-antenna arrays, whereas the mobile users' terminals are based on simple single antenna structures having also power restrictions. Therefore, cooperative protocols may be developed aiming to improve the quality / reduce the required power of the uplink transmissions by employing single-antenna relay nodes. These relay nodes may be fixed low-cost base stations or single-antenna users in the vicinity of the user who wants to establish uplink communication with the multi-antenna destination.

The motivation behind the present work is to develop uplink cooperative techniques for half duplex systems that achieve improved multiplexing and diversity gain compared to existing approaches. The techniques are developed by applying single-antenna node cooperation in order to create a virtual MIMO system along with the multi-antenna base-station. The performance of the new techniques is evaluated by deriving the outage probability and the Diversity-Multiplexing Tradeoff they achieve. The contributions of the presented paper are the following ones.

At first, we further develop and evaluate the performance of the uplink cooperative transmission technique suggested in [29] for DF cooperative systems. The proposed technique exploits properly the structure of the virtual MIMO channel matrix [1] to create multiple independent channels (singular channels) through which multiple symbols are transmitted simultaneously to the destination in one timeslot. In [29] only the DMT curve of the scheme was derived. In the present paper we derive the exact outage probability of the proposed scheme. The outage probability is a well-known performance metric used to evaluate the performance of communication systems in fading channels. During the past years, several works in literature dealt with the evaluation of the outage behaviour of different relaying approaches (see [30]-[36] and the references therein). Moreover, a more rigorous derivation of the DMT curve is also given. Furthermore, in the present paper more insight on the technique's performance is gained by providing more detailed simulations that include several cases for different parameters' values (i.e. fading) and comparisons to the performance of existing schemes and to the one of a non cooperative SIMO system. As it is shown, the proposed technique achieves greater diversity than a SIMO system in which each user transmits without cooperation its data to the multi-antenna destination and greater multiplexing gain than the conventional DF protocol of [4]. In fact, it is noteworthy that the system is able to choose among different options concerning the achieved diversity and multiplexing gain by properly configuring its parameters. That is, the proposed technique is among the most flexible ones since most of the existing techniques exhibit fixed diversity and multiplexing gains.

In order to improve further the performance, the proposed technique has been extended so as to accommodate multiple users [29]. Provided that a number of potential users (source nodes) are willing to communicate with the base station (destination node) a novel user selection criterion is proposed. The concept of opportunism has been previously used extensively in the cooperative system's literature via the so-called relay selection techniques [37]-[39]. By employing such techniques the performance of a cooperative technique is improved since only relay(s) with relative good channel(s) condition (according to a criterion) are used for forwarding the source node's data. In the present paper we further extend the opportunistic approach of [29] incorporating relay selection mechanisms in a way such that the proposed technique exploits both kinds of opportunism i.e., best user selection and best subset of relays selection. Novel criteria are suggested for selecting the best transmitting user and/or the best relays at each time slot. It is noteworthy that the resulting cooperative technique is the first one that exploits both kinds of opportunism, to the best of our knowledge. The performance of the opportunistic technique is evaluated theoretically and by representative simulations as well.

The rest of the paper is organized as follows. In Section II, the proposed technique is described. In Section III we present the corresponding theoretical performance analysis. Section IV presents the opportunistic extension of the proposed technique. In Section V the corresponding theoretical performance analysis of the opportunistic technique is given. In Section VI, representative simulation results are shown and discussed, and finally, Section VII concludes the work.

II. System's Description

In this section the system description is given. Let us consider a system with a single-antenna source and a M antenna destination, and let us also assume that N relays are available to participate in a cooperative transmission scheme.

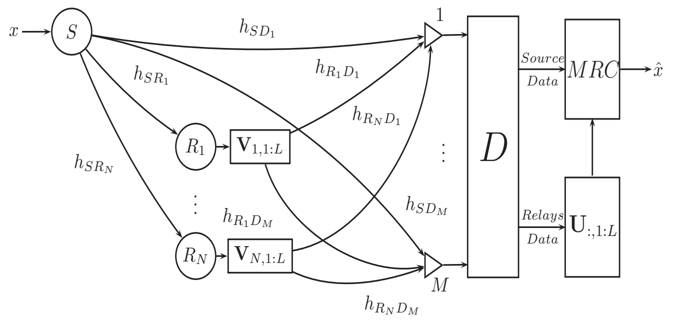

Fig. 1: The proposed technique.

$S \to R_{1\ldots N}$, $S \to D$	$R_{1\ldots N} \to D$
T_1	T_2

Table 1: Medium access control.

The relays are assumed to be other adjacent users that help the scheduled one to transmit its data to the destination via employing a cooperative transmission protocol or cheaper single-antenna base stations that are deployed within the cell. The idea is based on the fact, that each user can find other nodes (other users or the cheaper base stations) in its close proximity with which it shares strong channels and form a virtual MIMO system with the multiple antennas of the base station (destination) in order to improve the quality of the uplink transmission.

Let us now proceed to the system description. A system with N relays and M antennas at the receiver is depicted in Figure 1.1. The time frame is divided into two periods (see Table 1). During time period T_1 the source transmits L symbols $x\left(n\right),\ 1 \leq n \leq L \in [1, \min\left\{M, N\right\}]$, in L consecutive time slots, to the N relays and to the destination. For the $n-th$ symbol, the samples received at the destination and the relay nodes are given by

$$\mathbf{y}_D\left(n\right) = \sqrt{\frac{P_S}{2}}\mathbf{h}_{SD}x\left(n\right) + \mathbf{w}\left(n\right) \tag{1}$$

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

where $\mathbf{y}_D\left(n\right) = \left[y_{D_1}\left(n\right) \ \cdots \ y_{D_M}\left(n\right)\right]^T$ is the received vector at the destination, $\mathbf{h}_{SD} = \left[h_{SD_1} \cdots h_{SD_M}\right]^T$ is a vector containing the flat fading gains of the channels between the source and the destination antennas, h_{SR_i} is the tap of the flat fading channel between the source and the $i-th$ relay, $x(n)$ is the $n-th$ transmitted symbol, $\mathbf{w}\left(n\right) \in \mathcal{C}^{M\times 1}$and $w_i\left(n\right) \in \mathcal{C}$ are variables of complex additive noise of variance σ_w^2 modelled as $\mathcal{CN}(0, \sigma_w^2)$ and P_S is the power constraint of the source node. It is assumed that the involved channels undergo Rayleigh block fading with block size equal to $L+1$ time symbols. The corresponding flat fading coefficients capture the effects of path-loss and shadowing and they are modelled as $\mathcal{CN}(0, \gamma_{SR_i}^2)$, $\mathcal{CN}(0, \gamma_{SD}^2)$ and $\mathcal{CN}(0, \gamma_{R_iD}^2), 1 \leq i \leq N$ for the source-relays, source-destination and the relays-destination channels respectively. As it was described, we assume in general that the relays are other adjacent users or single antenna cheap base stations that help the source to transmit its information to the base station (destination). Therefore, from now and on, we assume that $\gamma_{R_iD}^2 = \gamma_{SD}^2, \forall i$ and $\gamma_{SR_i}^2 = \gamma_{SR}^2, \forall i$ for simplicity. The relay nodes detect the symbols based on the received signals described by (2), and subsequently, at the $L+1$ time slot (period T_2 in Figure 1.2), the relays that have correctly detected all the L symbols forward them simultaneously to the destination. Let us denote with K the number of the relays that exhibit an outage event, then the number of the remaining relays that can correctly decode all the symbols must be at least L, that is $N-K \geq L$. The latter inequality stems from the fact that the number of the non-zero singular values (which corresponds to the number of available parallel independent channels in the proposed technique) of a $M \times (N-K)$ matrix is $\min\{N-K, M\}$ [1][40] and therefore the number of the relays that do not exhibit an outage event indicates the available parallel singular channels. In case that $N-K < L$, we assume for simplicity, that the relays do not forward any symbol at all and only the direct source-destination transmission path is used. Note that the assumption that a relay knows if a symbol is correctly detected in the DF protocol case, is typical in the relevant literature [4]. In Remark 1 further comments will be given for this requirement.

Let us now assume that $N-K \geq L$, so that there are $N-K$ relays that have correctly detected all the L symbols and therefore they are able to forward a superposition of them (Fig. 1). The $i-th$ relay's superposition weights are the first L elements of the $i-th$ row of the right singular vectors' matrix $\mathbf{V}_{1:N,1:L}$. The latter is computed by the SVD of the virtual $M \times (N-K)$ MIMO channel matrix

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

where $h_{R_iD_j} \sim \mathcal{CN}(0, \gamma_{RD}^2)$ is the tap of the channel between the $i-th$ relay and the $j-th$ destination antenna. Thus, during the transmission period T_2 the received samples at the destination node are

$$\mathbf{y}_D\left(L+1\right) = \sqrt{\frac{P_S}{2}}\mathbf{H}_{RD}\mathbf{x}'\left(L+1\right) + \mathbf{w}\left(L+1\right) \tag{4}$$

where $\mathbf{x}'\left(L+1\right) = \mathbf{V}_{1:N,1:L}\mathbf{x}\left(L+1\right)$, $\mathbf{H}_{RD} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$, $\mathbf{x}\left(L+1\right) = \left[\hat{x}\left(1\right), \cdots, \hat{x}\left(L\right)\right]^T$is a vector with the L symbols, and $\mathbf{w}\left(L+1\right) \in \mathcal{C}^{M\times 1}$. 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

$$\begin{aligned} \mathbf{y}'_D &= \mathbf{U}_{1:M,1:L}^H\mathbf{y}_D\left(L+1\right) \\ &= \sqrt{\frac{P_S}{2}}\mathbf{\Sigma}_L\mathbf{x}\left(L+1\right) + \mathbf{w}'\left(L+1\right), \end{aligned} \tag{5}$$

where $\mathbf{\Sigma}_L$ is the upper diagonal matrix of $\mathbf{\Sigma}$ containing the L first (ordered) singular values of matrix $\mathbf{H}_{RD}$ and $\mathbf{w}'\left(L+1\right) \in \mathcal{C}^{L\times 1}$ due to the singular vectors' unitary property. Thus, the $N-K$ relays that correctly decoded

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all the L symbols form with the M destination antennas a virtual MIMO system via which the L symbols are transmitted. The transmission is done via the corresponding independent parallel singular channels employing an equal power allocation strategy. Of course the performance of the proposed technique can be further improved by employing a water-filing based power allocation approach at the relays-to destination transmission [1], though for simplicity we consider here the equal power allocation strategy only. Now, note that the $i-th$ channel gain is equal to the $i-th$ singular value. Since the singular values are independent of the taps h_{SD_i} we can use a combination of eq.(1) and eq.(5) to extract higher diversity gain. More precisely, for each symbol that was correctly detected from the $N-K$ relays we have M transmission paths from (1) and one path from (5). The latter path is the corresponding singular channel which contributes implicitly to the overall diversity gain. Thus, Maximum Ratio Combining (MRC) can be applied on the equivalent SIMO system, i.e.,

$$\mathbf{y}_D^i = \mathbf{h}_{eq}^i \mathbf{x}_i + \mathbf{w}_i, \quad 1 \le i \le L \tag{6}$$

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 $\mathbf{y}'_D$, σ_i is the $i-th$ singular value, $\mathbf{h}_{eq}^i = \sqrt{\frac{P_S}{2}}\left[\mathbf{h}_{SD}^T, \sigma_i\right]^T$, $\mathbf{w}_i = \left[\mathbf{w}^T(i), w'_i(L+1)\right]^T$ and $w'_i(L+1)$ is the $i-th$ element of $\mathbf{w}'(L+1)$.

Remark 1: As it is stated in this section, the relays should acknowledge the other ones and the destination node if they will participate in the transmission period T_2. Similar assumptions (see [41] and references therein) are also typical in the literature of distributed space-time coding for cooperative networks where the problem is tackled by assuming 1-bit acknowledgement broadcasts from each relay. In general, such a requirement seems to increase the complexity of the protocol, though control channels similar to the ones required here, are constituent part of wireless communication systems for several functionalities within the network, such as power control, handover, routing e.t.c [42]. Let us now get into more detail. Each relay is related to one 1-bit control channel which sets to a state if it detects an error in one of the L received symbols. Therefore the other relays and the destination node are acknowledged that the latter relay will not be able to participate during transmission phase T_2, according to the protocol description given in the present section. The control information can be assumed to be transmitted without errors e.g. due to the low rate requirements. Thus, if every relay and the destination node have access to the data of all the N channels, they can be aware of the relays network status at every timeslot.

Remark 2: Let us briefly comment on the CSI requirements of the protocol. According to the description given in this section, the source node requires no CSI information, each one of the relays requires the knowledge of the corresponding row of the right singular vectors matrix $\mathbf{V}$, and the destination node requires the left singular vectors matrix $\mathbf{U}$ and the source to destination channel gain vector $\mathbf{h}_{SD}$. Let us recall that matrices $\mathbf{V}$ and $\mathbf{U}$ are computed by the SVD of the relays to destination matrix $\mathbf{H}_{RD}$. The vector $\mathbf{h}_{SD}$ can be estimated by pilot symbols transmitted from the source, similar to a SIMO channel case. The intriguing part here is how the required rows of matrix $\mathbf{V}$ are estimated at each one of the relay nodes. A simple approach would be to transmit training symbols from the relays to the destination node so as the latter one to estimate both matrices $\mathbf{V}$ and $\mathbf{U}$ and then feedback the required rows of matrix $\mathbf{V}$ to the corresponding relays. It is noteworthy that these two singular vector matrices can be estimated in a totally blind matter by applying subspace tracking methods. In fact, it can be shown that, given that the destination node transmits data to the relay ones and that the channel reciprocity assumption is valid, each relay can update in a blind and decentralized adaptive manner the corresponding row of matrix $\mathbf{V}$ [43]. A more detailed discussion is beyond the scopes of the present paper. Apart from these two approaches there is also the possibility of using codebooks for matrices $\mathbf{V}$ and $\mathbf{U}$. The codebook approach could be very practical due to the dynamic nature of the relays network which is a result of the decoding errors at the relays, as it was described in the system description area. Codebook design based on Grassmannian Beamforming [44]-[45] is commonly adopted in parallel decomposition MIMO schemes as a means to cope with the CSI requirements of matrix $\mathbf{V}$. According to the fading state, the receiver feedbacks to the transmitter an index that corresponds to an entry in his codebook which has the appropriate values for the precoding matrix $\mathbf{V}$. In a similar way, the relays could keep a codebook of the desired row of matrix $\mathbf{V}$ and choose the corresponding values for its entries according to the number of the relays that participate in the transmission phase T_2 and to the fading state of the channel, resulting in a simple and a practical implementation of the proposed approach.

III. Performance Analysis

In this section theoretical results concerning the performance of the proposed scheme are derived. At first the outage probability of the technique is derived. Then the corresponding DMT curve is computed.

A. Outage Probability Analysis

The following theorem provides the theoretical outage probability of the technique under Rayleigh fading.

Theorem 1: The outage probability of the proposed technique for a system with M destination antennas, N relays, block size L and targeted data rate R bits/sec under Rayleigh fading conditions is given by

$$P_{out} = \sum_{K=0}^{N-L} \binom{N}{K} \left(1 - e^{-\frac{2^R-1}{0.5\gamma_{SR}^2 \xi}}\right)^K e^{-\frac{\left(2^R-1\right)(N-K)}{0.5\gamma_{SR}^2 \xi}} \times$$
$$\left(\frac{1}{0.5\gamma_{SD}^2}\right)^M \left(\frac{1}{0.5\gamma_{SD}^2 \bar{\lambda}_L}\right)^{\beta(K)} \times$$
$$G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c} \mathbf{\Psi}_1 \\ \mathbf{\Psi}_2 \end{array} \middle| , e^{-\frac{2^R-1}{\xi}}\right) +$$
$$\sum_{K=N-L+1}^{N} \binom{N}{K} \left(1 - e^{-\frac{2^R-1}{0.5\gamma_{SR}^2 \xi}}\right)^K e^{-\frac{\left(2^R-1\right)(N-K)}{0.5\gamma_{SR}^2 \xi}} \times$$

$$\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SD}^2\xi}}\sum_{m=0}^{M-1}\frac{\left(\frac{2^R-1}{0.5\gamma_{SD}^2\xi}\right)^m}{m!}\right) \tag{7}$$

where $\xi = \frac{P_S}{\sigma_w^2}$, $\bar{\lambda}_L$ is the mean of the squared eigenvalue of matrix $\mathbf{H}_{RD}$ when its entries are distributed as $\mathcal{CN}(0,1)$, $\beta(K) = (N-K-L+1)(M-L+1)$, $G_{p,q}^{m,n}$ is the so-called MeijerG function [46] having the vector operands $\mathbf{\Psi}_1$ and $\mathbf{\Psi}_2$ defined as

$$\mathbf{\Psi}_1 = \left[\underbrace{\left(1+\frac{1}{0.5\gamma_{SD}^2}\right),\ldots,\left(1+\frac{1}{0.5\gamma_{SD}^2}\right)}_{M-terms},\right.$$

$$\left.\underbrace{\left(1+\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right),\ldots,\left(1+\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)}_{\beta(K)-terms},1\right]$$

$$\mathbf{\Psi}_2 = \left[\underbrace{\left(\frac{1}{0.5\gamma_{SD}^2}\right),\ldots,\left(\frac{1}{0.5\gamma_{SD}^2}\right)}_{M-terms},\right.$$

$$\left.\underbrace{\left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right),\ldots,\left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)}_{\beta(K)-terms},0\right], \tag{8}$$

respectively.

Proof: Let us first provide some notations. The outage probability of an $1\times M$ MIMO system for a given rate R is defined as

$$P_{out}(R) = P\left\{\log\left(1+\|\mathbf{h}\|^2\xi\right) < R\right\} = F_\eta\left(\frac{2^R-1}{\xi}\right) \tag{9}$$

where $F_\eta(\cdot)$ is the Cumulative Distribution Function (CDF) of the Random Variable (RV) $\eta = \|\mathbf{h}\|^2$. $P_{(K)}$ and $\overline{P_{(K)}}$ denote the probability that an outage event occurs and does not occur in K relays, respectively, $P_{out}^{eq(N-K)}$ is the outage probability of the overall equivalent system of eq. (6) when $N-K\geq L$ relays do not exhibit an outage event, P_{out}^{SIMO} denotes the outage probability of the generic SIMO system consisted only of the direct paths between the source and the destination antennas when $N-K<L$, and P_{out}^{SISO} is the outage probability of a SISO system (as the one between the source and a relay). We claim that the outage probability of the proposed technique can be expressed as

$$P_{out} = \sum_{K=0}^{N-L}\binom{N}{K}P_{(K)}\left(\overline{P_{(N-K)}}\right)P_{out}^{eq(N-K)} + \sum_{K=N-L+1}^{N}\binom{N}{K}P_{(K)}\left(\overline{P_{(N-K)}}\right)P_{out}^{SIMO}. \tag{10}$$

Observe that equation (10) consists of two sums that correspond to the two distinct cases that appear when the technique is applied. As it was described in Section II, the relays forward the data during the phase T_2 if the number of the relays that correctly decoded the source data are $N-K\geq L$. In this case the equivalent system of eq.(6) is used for symbol detection at the destination. Therefore, one can compute the outage probability of the system by weighting the outage probability of the last system by the probability that exact K relays exhibit an outage event, given by $\binom{N}{K}P_{(K)}\left(\overline{P_{(N-K)}}\right)$, where the binomial term $\binom{N}{K}$ is used to count for all the possible combinations of K relays, and taking the summation for $0\leq K\leq N-L$. Therefore, the first sum of the eq.(10) is derived. By following the same procedure one can derive also the second sum of eq.(10) that corresponds to the case in which $N-K<L$. In this case the number of the relays that have correctly decoded all the symbol is not sufficient to forward the data to the destination node and therefore none of them transmits during the transmission period T_2. That is, the destination relies only on the transmission of period T_1 for the symbol detection and the outage probability of the system equals to the one of a SIMO one having M receiver antennas.

Let us now proceed further with the proof. As it is evident both of the sum terms of eq.(10) include the term $\binom{N}{K}P_{(K)}\left(\overline{P_{(N-K)}}\right)$ which as it was already stated equals the probability that exactly K out of the N relays exhibit an outage event during the source-relays transmission phase T_1. If we assume that the relays have independent fading channel coefficients the outage event at exactly K relays can be expressed as

$$\binom{N}{K}P_{(K)}\left(\overline{P_{(N-K)}}\right) = \binom{N}{K}\left(P_{out}^{SISO}\right)^K\left(1-P_{out}^{SISO}\right)^{N-K}$$
$$= \binom{N}{K}\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}^2\xi}}\right)^K e^{-\frac{\left(2^R-1\right)(N-K)}{0.5\gamma_{SR}^2\xi}} \tag{11}$$

where we have used the formula $P_{out}^{SISO} = 1-e^{-\frac{2^R-1}{0.5\gamma_{SR}^2\xi}}$ [47] that gives the outage probability of a SISO system having the same fading parameters and transmission power to the ones considered in the source-relays transmission period T_1.

Let us, now consider the case in which $N-K<L$ As it was already described, the outage probability of the system equals to the one of a SIMO one having M receiver antennas. For the given fading conditions and source power transmission, the latter probability according to [47] is given by

$$P_{out}^{SIMO} = 1-e^{-\frac{2^R-1}{0.5\gamma_{SD}^2\xi}}\sum_{m=0}^{M-1}\frac{\left(\frac{2^R-1}{0.5\gamma_{SD}^2\xi}\right)^m}{m!}. \tag{12}$$

In order to complete the proof, we finally need to derive the outage probability of the equivalent system of eq.(6) $P_{out}^{eq(N-K)}$ when $N-K\geq L$. Since in the destination a MRC scheme is applied on the equivalent parallel independent channels $\mathbf{h}_{eq}^i, 1\leq i\leq L$, the received SNR can be expressed as $\|\mathbf{h}_{eq}^i\|^2\xi, 1\leq i\leq L$. Now according to system description we have that

$$\begin{aligned}\|\mathbf{h}_{eq}^i\|^2 &= 0.5\left(|h_{SD_1}|^2+\cdots+|h_{SD_M}|^2\right)+0.5\sigma_i^2\\ &= 0.5\|\mathbf{h}_{SD}\|^2+0.5\sigma_i^2, 1\leq i\leq L.\end{aligned} \tag{13}$$

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Eq.(13) is a sum of positive terms and thus one can see that $\|\mathbf{h}_{eq}^L\|^2 \leq \|\mathbf{h}_{eq}^{L-1}\|^2 \leq \cdots \leq \|\mathbf{h}_{eq}^1\|^2$ due to the fact that $0 \leq \sigma_L \leq \sigma_{L-1} \leq \cdots \leq \sigma_1$. The following observation leads to the conclusion that the outage probability of the equivalent system equals the outage probability of its weakest, in terms of the received SNR channel, that is the one involving the $L-th$ eigenvalue. Thus, in order to compute the required outage probability the distribution of the scalar $\|\mathbf{h}_{eq}^L\|^2$ Random Variable (RV) must be derived. Now observe the second equation of eq.(13). The RV $\chi = 0.5\|\mathbf{h}_{SD}\|^2$ is a scaled sum of squared RVs distributed as $\mathcal{CN}(0,\gamma_{SD}^2)$ and therefore has CDF given by

$$F_\chi(x) = 1 - e^{-\frac{x}{0.5\gamma_{SD}^2}} \sum_{m=0}^{M-1} \frac{\left(\frac{x}{0.5\gamma_{SD}^2}\right)^m}{m!}. \tag{14}$$

Note that, the outage of SIMO system given at eq.(12) is derived by evaluating the CDF of eq.(14) at point $\frac{2^R-1}{\xi}$. Moreover, for the RV $\psi = 0.5\sigma_i^2$ we can use the results of [48] that concern the marginal distribution of the $L-th$ squared eigenvalue of a MIMO channel under Rayleigh fading, $\mathcal{CN}(0,\gamma_{SD}^2)$, and derive the corresponding CDF which is given by

$$F_\psi(y) = 1 - e^{-\frac{y}{0.5\gamma_{SD}^2}} \sum_{m=0}^{\beta(K)-1} \frac{\left(\frac{y}{0.5\gamma_{SD}^2}\right)^m}{m!}. \tag{15}$$

From eqs.(14)-(15), it is evident that the RV $\zeta = \|\mathbf{h}_{eq}^L\|^2$ is the sum of the independent RVs χ and ψ which follow the gamma distribution with different parameters each one. By using the results of [49] we can show that the CDF of the RV ζ is given by

$$F_\zeta(z) = \left(\frac{1}{0.5\gamma_{SD}^2}\right)^M \left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)} \times G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c}\boldsymbol{\Psi}_1\\ \boldsymbol{\Psi}_2\end{array}\middle|, e^{-z}\right) \tag{16}$$

where the vector operands $\boldsymbol{\Psi}_1$ and $\boldsymbol{\Psi}_2$ were defined at eq.(8). Finally, by evaluating the CDF of eq.(16) at $\frac{2^R-1}{\xi}$ we get the required outage probability of the equivalent system given by

$$P_{out}^{eq(N-K)} = \left(\frac{1}{0.5\gamma_{SD}^2}\right)^M \left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)} \times G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c}\boldsymbol{\Psi}_1\\ \boldsymbol{\Psi}_2\end{array}\middle|, e^{-\frac{2^R-1}{\xi}}\right). \tag{17}$$

Now by plugging in the results of eqs.(11), (12) and (17) into eq.(10) we get eq.(7) which completes the proof. ■

B. Diversity-Multiplexing Tradeoff Analysis

Let us now proceed to the Derivation of the DMT curve of the proposed scheme. According to [50], the diversity gain for a target rate $R = r\log_2(\xi)$ where we remind $\xi = \frac{P_S}{\sigma_w^2}$ is the transmission SNR, is defined as

$$d(r) = -\lim_{\xi\to\infty} \frac{\log_2(P_e(\xi))}{\log_2(\xi)} \tag{18}$$

where $P_e(\xi)$ is the error probability for the given SNR and r is the multiplexing gain. In [50] the authors used the fact that a communication can be always error free by setting the rate lower than the capacity of the channel so as to avoid an outage event to lower bound the error probability by the outage one. That is,

$$\lim_{\xi\to\infty} \frac{\log_2(P_e(\xi))}{\log_2(\xi)} \geq \lim_{\xi\to\infty} \frac{\log_2(P_{out}(\xi))}{\log_2(\xi)}. \tag{19}$$

Therefore, based again on [50], the following definition for the diversity gain is used that employs the outage probability $P_{out}(\xi)$ instead of the error one $P_e(\xi)$

$$d(r) = -\lim_{\xi\to\infty} \frac{\log_2(P_{out}(\xi))}{\log_2(\xi)}. \tag{20}$$

The following theorem provides the DMT curve of the proposed scheme

Theorem 2: The DMT curve of the proposed technique is given by

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

Proof: The outage probability for the targeted data rate $R = r\frac{L+1}{L}\log_2(\xi)$ is given according to eq.(7) by

$$\begin{aligned} P_{out} = &\sum_{K=0}^{N-L}\binom{N}{K}\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}\right)^K \times \\ &e^{-\frac{(N-K)\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}\left(\frac{1}{0.5\gamma_{SD}^2}\right)^M\left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)} \times \\ &G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c}\boldsymbol{\Psi}_1\\ \boldsymbol{\Psi}_2\end{array}\middle|, e^{-\xi^{-\left(1-\frac{L+1}{L}r\right)}}\right) + \\ &\sum_{K=N-L+1}^{N}\binom{N}{K}\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}\right)^K e^{-\frac{(N-K)\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}} \times \\ &\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}}\sum_{m=0}^{M-1}\frac{\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}\right)^m}{m!}\right). \end{aligned} \tag{22}$$

Note that the data rate r is scaled by a factor $(L+1)/L$ due to the fact that the proposed cooperative scheme requires $L+1$ timeslots to transmit L symbols.

Let us now inspect the terms of eq.(22) and identify their corresponding order of decay as $\xi \to \infty$. As it was already mentioned before, both the two distinct sum operators include the term

$$\left(1-e^{-\frac{\xi^{-(1-\frac{L+1}{L}r)}}{0.5\gamma_{SR}^2}}\right)^K e^{-\frac{\xi^{-(1-\frac{L+1}{L}r)}}{0.5\gamma_{SR}^2}}.$$

Now, as $\xi \to \infty$ we have

$$\lim_{\xi\to\infty} e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}} = 1 \tag{23}$$

and

$$\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}\right)^K \approx \left(0.5\gamma_{SR}^2\right)^{-K}\xi^{-K\left(1-\frac{L+1}{L}r\right)} \quad (24)$$

where the Taylor series expansion formula of $(1-e^{-x}) = x+\mathcal{O}(x^2)$ around 0 was used. Moreover according to [1], the outage probability of the SIMO channel can be approximated for the same target rate R as $\xi \to \infty$ by the following equation

$$1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}}\sum_{m=0}^{M-1}\frac{\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}\right)^m}{m!} \approx \left(0.5\gamma_{SD}^2\right)^{-M}\xi^{-M\left(1-\frac{L+1}{L}r\right)}. \quad (25)$$

It remains to seek for a simplified expression for the term

$$P_{out}^{eq(N-K)} = \left(\frac{1}{0.5\gamma_{SD}^2}\right)^M\left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)} \times G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c}\mathbf{\Psi}_1\\ \mathbf{\Psi}_2\end{array}\middle|, e^{-\xi^{-\left(1-\frac{L+1}{L}r\right)}}\right) \quad (26)$$

as $\xi \to \infty$. By using the results of [51] one can rewrite $P_{out}^{eq(N-K)}$ as

$$P_{out}^{eq(N-K)} = \frac{\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}\right)^M\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)}}{\Gamma\left(1+M+\beta(K)\right)} \times \mathbf{\Phi}_2^{(2)}\left(M,\beta(K);1+M+\beta(K);\frac{-\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2},-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right) \quad (27)$$

where $\Gamma(\cdot)$ is the Gamma function and $\mathbf{\Phi}_2^{(2)}$ is the confluent Lauricella multivariate hypergeometric function defined in [52]-[53]. Now by using the equivalence of the latter function with the Appell hypergeometric one [52] we can rewrite eq.(27) as

$$P_{out}^{eq(N-K)} = \frac{\xi^{-(M+\beta(K))\left(1-\frac{L+1}{L}r\right)}}{\Gamma\left(1+M+\beta(K)\right)\gamma_{SD}^{2M}0.5^M\gamma_{SD}^{2\beta(K)}0.5^{\beta(K)}\bar{\lambda}_L^{\beta K}} \times \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{(M)_m\left(\beta(K)\right)_n\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2}\right)^m\left(\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^n}{m!n!\left(1+M+\beta(K)\right)_{m+n}} \quad (28)$$

where $(\alpha)_k = \frac{\Gamma(\alpha+k)}{\Gamma(\alpha)}$ is the Pochammer symbol. The outage probability is dominated by the largest exponent of ξ as $\xi \to \infty$ which is given by setting $m=0$ and $n=0$ in the double infinite series sum of eq.(28), that is

$$P_{out}^{eq(N-K)} \approx \frac{\xi^{-(M+\beta(K))\left(1-\frac{L+1}{L}r\right)}}{\Gamma\left(1+M+\beta(K)\right)\gamma_{SD}^{2M}\gamma_{SD}^{2\beta(K)}0.5^{M+\beta(K)}\bar{\lambda}_L^{\beta(K)}} \quad (29)$$

Now by plugging eqs.(24), (25) and (29) into eq.(22) we have as $\xi \to \infty$

$$P_{out} \approx \sum_{K=0}^{N-L}\binom{N}{K}\left(0.5\gamma_{SR}^2\right)^{-K}\xi^{-K\left(1-\frac{L+1}{L}r\right)} \times \frac{\xi^{-(M+\beta(K))\left(1-\frac{L+1}{L}r\right)}}{\Gamma\left(1+M+\beta(K)\right)\gamma_{SD}^{2M}0.5^M\gamma_{SD}^{2\beta(K)}0.5^{\beta(K)}\bar{\lambda}_L^{\beta(K)}} + \sum_{K=N-L+1}^{N}\binom{N}{K}\left(0.5\gamma_{SR}^2\right)^{-K}\xi^{-K\left(1-\frac{L+1}{L}r\right)} \times \left(0.5\gamma_{SD}^2\right)^{-M}\xi^{-M\left(1-\frac{L+1}{L}r\right)} \quad (30)$$

It is evident that the outage probability of eq.(30) is dominated by the term having the largest exponent of ξ. Thus, by inspecting the later equation one can see that the term that dominates the decaying speed of the outage probability of the system as $\xi \to \infty$ is the

$$\binom{N}{K}\left(0.5\gamma_{SR}^2\right)^{-K}\xi^{-K\left(1-\frac{L+1}{L}r\right)}\left(0.5\gamma_{SD}^2\right)^{-M}\xi^{-M\left(1-\frac{L+1}{L}r\right)}$$

one for $K=N-L+1$. Therefore, by combining the previous result with the definition of the DMT (20), we obtain the DMT curve of eq.(44) and the proof is completed. ■

IV. The Multi-User Case with Relay Selection: System Description

In this section the proposed technique is extended to a multi-user scenario by employing at the same time a relay selection technique so as to achieve improved performance by exploiting both kinds of opportunism. Opportunistic techniques were firstly appeared in multi-user systems [1], where a diversity gain (multiuser diversity) was achieved by scheduling for communication at every time slot the best user, according to a proper criterion. In cooperative systems a similar concept of opportunism was introduced by the so-called relay selection techniques [38]. That is, the data are forwarded only through the best subset of relays according again to a proper selection criterion. That "proper" criterion is the key feature of the opportunistic communication techniques and depends highly on system's structure.

For simplicity, let us firstly consider only the multi-user scenario. That is, we assume that, at each time slot, there are W users trying to transmit, as well as a fixed set of N relays willing to help these users to transmit their data to the multi-antenna destination.

An appropriate selection criterion should involve the source - relays, the relays - destination and the source - destination channels through the equivalent channel $\mathbf{h}_{eq}^i$ defined in eq.(6). Recall that, in terms of diversity gain, the performance of the technique presented in Section II is governed by the condition of the channel $\mathbf{h}_{eq}^L$ corresponding to the $L-th$ singular value of the relays-destination matrix $\mathbf{H}_{RD}$ (see also Section III). Thus, according to [38], a reasonable criterion could schedule the user with the maximum harmonic mean of its worst source-relay channel gain and its equivalent channel $\mathbf{h}_{eq}^L$ as defined above. That is, the criterion selects the best user S^* such that

$$S^* = arg \max_i \left\{ \phi \left(\min_j \left| h_{S_i R_j} \right|^2 , \left\| \mathbf{h}^L_{eq_i} \right\|^2 \right) \right\} \tag{31}$$

where $1 \leq i \leq W$, $1 \leq j \leq N$ and function $\phi(\cdot,\cdot)$ computes the harmonic mean of its two operands. Note that the singular values that appear in the entries of the equivalent channel vector $\mathbf{h}_{eq}$ is the same for all the users. Thus, the above selection criterion is further simplified by considering only the users-destination channels in the computed harmonic mean.

It is evident that the previous criterion requires knowledge about the users (sources)-relays' channels and the users-destination channels. If we further extend the above criterion so as to incorporate relay selection capability into the system, the communication and computation overhead is even greater. This is due to the fact that, under the assumption that Q additional relays are available, a suitable criterion for the selection of N relays, out of the $N+Q$ available, requires knowledge concerning the SVD of $\binom{N+Q}{N}$ candidate relays-destination matrices for each user.

In order to provide a more practical opportunistic strategy, simple selection criteria are proposed that are based on the users(sources)-relays channels. This approach is of course sub-optimal and appropriate only for small-scale fading environments though, as it is shown, it provides significant performance improvement and its theoretical analysis is tractable.

Thus, from the above discussion concerning the "best" user selection criterion, it is evident that the "weak" links of the relays-based system are the involved SISO channels, that is, the source-relays channels. Recall that the outage probability of a SISO channel decays very slowly, as $1/SNR$. Thus, an opportunistic selection strategy would be to choose the user with the best user-relays channel. Obviously, each user is connected via SISO links to each one of the N relays. Since the worst of these N links is the one that actually determines the performance of the user-relays system, it is reasonable to choose the user whose worst channel is the best among all W users. Furthermore, it can be easily verified that $P_{out}^{SISO} >> P_{out}^{SIMO}$ as the number of the destination antennas M increases, that is, the overall system performance is actually affected by the user-relays links. Therefore, for simplicity, and assuming that all channel gains follow the same distribution, the users are scheduled according to the quality of the worst user-relay channel. In other words, at each time slot, the transmitting user is the one whose worst user-relay channel has the best quality.

More formally, the criterion for selecting the best user S^* out of the W users is given by

$$S^* = arg \max_i \left\{ \min_j \left\{ \left| h_{S_i R_j} \right|^2 \right\} \right\} \tag{32}$$

where $1 \leq i \leq W$ and $1 \leq j \leq N$.

Let us now incorporate the relay selection technique in the above system. That is, the combined cooperative scheme consists of W users (sources), $N+Q$ relays and a destination of M antennas. The aim is again to transmit L consecutive symbols through the associated $N \times M$ virtual MIMO system. Following the analysis of the multi-user only case, a suitable criterion should be the one that schedules for transmission the best user with the best subset of N relays. Thus at first, each user selects the best subset of N relays $\mathbf{R}^*_j = \left\{ R^*_{1j}, \ldots, R^*_{Nj} \right\}$ by,

$$\mathbf{R}^*_j = arg \left\{ \max_{N:N+Q} \left\{ |h_{SR_i}|^2 \right\} \right\}, \; 1 \leq i \leq N+Q \;, \tag{33}$$

where with the $\max_{N:N+Q}$ we denote the N random variables that have the largest N values out of a set of $N+Q$ random variables in a specific realization. Then, according to the criterion of (32), the user with the best worst source-relays channel is selected. Thus, the combined selection criterion is defined as

$$\mathbf{S}^* = arg \max_j \left\{ \min_i \left\{ |h_{S_j R^*_{ji}}|^2 \right\} \right\} \tag{34}$$

where $1 \leq i \leq W$ and $1 \leq j \leq N$. In the following section the performance analysis for the above scheme is provided.

V. The Multi-User Case with Relay Selection: Performance Analysis

Unfortunately the user/relays' selection criteria complicate a lot the performance analysis and therefore it is not possible to derive the exact outage probability of the opportunistic extension of the technique. Nevertheless we derive one lower and one upper bound for the outage probability and the corresponding DMT curve of the scheme.

A. Outage Probability Analysis

The following theorem provides one upper and one lower bound for the outage probability of the proposed scheme.

Theorem 3: An upper bound on the outage probability of the opportunistic extension of the proposed technique for a system with M destination antennas, N relays, block size L, W users, Q surplus relays and targeted data rate R bits/sec under Rayleigh fading conditions is given by

$$\begin{aligned} P_{out} \leq & \sum_{K=0}^{N-L} \binom{N}{K} \left[\sum_{j=N}^{N+Q} \binom{N+Q}{j} \times \right. \\ & \left. \left(1 - e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}} \right)^{N+Q-j} e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}} \right]^{KW} \times \\ & \left\{ 1 - \left[\sum_{j=N}^{N+Q} \binom{N+Q}{j} \times \right. \right. \\ & \left. \left. \left(1 - e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}} \right)^{N+Q-j} e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}} \right]^{W} \right\}^{N-K} \times \\ & \left(\frac{1}{0.5\gamma_{SD}^2} \right)^M \left(\frac{1}{0.5\gamma_{SD}^2 \bar{\lambda}_L} \right)^{\beta(K)} \times \\ & G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1} \left(\begin{array}{c} \mathbf{\Psi}_1 \\ \mathbf{\Psi}_2 \end{array} \middle| , e^{-\frac{2^R-1}{\xi}} \right) + \end{aligned}$$

$$\sum_{K=N-L+1}^{N}\binom{N}{K}\left[\sum_{j=N}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{KW}\times$$
$$\left\{1-\left[\sum_{j=N}^{N+Q}\binom{N+Q}{j}\times\right.\right.$$
$$\left.\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{W}\right\}^{N-K}\times$$
$$\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SD}^2\xi}}\sum_{m=0}^{M-1}\frac{\left(\frac{2^R-1}{0.5\gamma_{SD}^2\xi}\right)^m}{m!}\right). \tag{35}$$

A corresponding lower bound is given by

$$P_{out}\geq\sum_{K=0}^{N-L}\left[\sum_{j=N+K}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{W}\times$$
$$\left(\frac{1}{0.5\gamma_{SD}^2}\right)^M\left(\frac{1}{0.5\gamma_{SD}^2\bar{\lambda}_L}\right)^{\beta(K)}\times$$
$$G^{\beta(K)+M+1,0}_{\beta(K)+M+1,\beta(K)+M+1}\left(\begin{array}{c}\boldsymbol{\Psi}_1\\ \boldsymbol{\Psi}_2\end{array}\middle|, e^{-\frac{2^R-1}{\xi}}\right)+$$
$$\sum_{K=N-L+1}^{N}\left[\sum_{j=N+K}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{W}\times$$
$$\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SD}^2\xi}}\sum_{m=0}^{M-1}\frac{\left(\frac{2^R-1}{0.5\gamma_{SD}^2\xi}\right)^m}{m!}\right). \tag{36}$$

Proof: At first the upper bound will be derived. Let us assume that the best user having the best subset of N relays is selected according to the criterion of eq.(34). Clearly, the outage probability of any channel between that user and its relays is upper bounded by the outage probability of its worse channel with a relay. Thus, according to eq.(11) we have that

$$P_{(K)}=\left(P_{out}^{SISO}\right)^K\leq\left(P_{out}^*\right)^K \tag{37}$$

where P_{out}^* denotes the outage probability of the worst source - relay channel of the scheduled user. Thus, in order to proceed further, we first require to derive the probability P_{out}^*.

Let $\mathbf{X}=\{X_1,\cdots,X_n\}$ be a vector of n i.i.d. random variables such that $X_i\sim F_\chi(x)$. The CDF of the maximum of the random variables, $Y=\max\{\mathbf{X}\}$, is given by

$$G(y)=F^n(y) \tag{38}$$

Moreover, the random variable $Z=\max_{k:n}\{\mathbf{X}\}$, which denotes the $k-th$ maximum of the variables X_i, has the following CDF

$$H_\zeta(z)=\sum_{j=k}^{n}\binom{n}{j}F_\chi(z)^{n-j}\left(1-F_\chi(z)\right)^j \tag{39}$$

where $F(x)$ and $f(x)$ denote the CDF and PDF, respectively, of X_i. Now recall that the source-to-relay links are via SISO channels whose fading gains are distributed according to the Rayleigh distribution as it was described in Section II. Recall that the CDF of these fading gains is given by

$$F(x)=1-e^{-\frac{x}{0.5\gamma_{SR}}}. \tag{40}$$

Now by plugging eq.(40) in eq.(39) and then the result in eq.(38) by using also eq.(9) it can be shown that the required outage probability P_{out}^* is given by

$$P_{out}^*(R)=\left[\sum_{j=N}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{W}. \tag{41}$$

Now by using eqs.(37) and (41) in eq.(10) the upper bound of eq.(35) is derived.

We can now move to the derivation of the lower bound. According to the criterion of eq.(34) the user (among the W ones) with the worst N-th source-to-relay channel is scheduled for transmission. Let us assume that an ideal system of N relays exist in which the i-th relay is the i-th, $1\leq i\leq N$ worst source-to-relay channel among the W users. That is, the source-relays channels are sorted for each user and then, for every $1\leq i\leq N$ we choose the best relay among the W available ones. Clearly, the performance of the latter ideal system lower bounds the performance of the opportunistic extension of the proposed technique. By following the same steps that led to the derivation of eq.(41) one can show that the outage probability of $i-th$ relay of the ideal system $P_{out}^{(i)}(R)$ is given by

$$P_{out}^{(i)}(R)=\left[\sum_{j=N+i}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{2^R-1}{0.5\gamma_{SR}\xi}}\right)^{N+Q-j}e^{-\frac{\left(2^R-1\right)j}{0.5\gamma_{SR}\xi}}\right]^{W}. \tag{42}$$

Now, an alternative way to derive the outage probability of the proposed technique given in eq.(10) is by observing that the probability that exactly K relays exhibit an outage event is equal to the outage probability of the K-th greatest relay, that is, the outage probability of the ideal system P_{out}^{ideal} can be expressed as

$$P_{out}^{ideal}=\sum_{K=0}^{N-L}P_{out}^{(K)}P_{out}^{eq(N-K)}+\sum_{K=N-L+1}^{N}P_{out}^{(K)}P_{out}^{SIMO} \tag{43}$$

where $P_{out}^{(K)}$ is given by eq.(42) for a targeted rate R. Finally, plugging in eqs.(12), (17) and (42) in eq.(43) the lower bound of eq.(36) is derived. ■

B. Diversity-Multiplexing Tradeoff Analysis

The following theorem provides the DMT curve of the opportunistic extension of the proposed scheme

Theorem 4: The DMT curve of the opportunistic extension of the proposed technique for a system with M destination antennas, N relays, block size L, W users and Q surplus relays is given by

$$d(r) = WQ(M+N-L+1)(1-r(L+1)/L). \tag{44}$$

Proof: The desired DMT curve can be derived by proving that both the upper and the lower bound of Theorem 3 correspond to the DMT curve given by eq.(44). The steps of the proof is identical to the ones of the Theorem 2, though in eq.(22) the term

$$\binom{N}{K}\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}\right)^K e^{-\frac{(N-K)\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}^2}}$$

is replaced by the

$$\binom{N}{K}\left[\sum_{j=N}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}}}\right)^{N+Q-j} e^{-\frac{\left(\xi^{-\left(1-\frac{L+1}{L}r\right)}\right)j}{0.5\gamma_{SR}}}\right]^{KW}\times$$
$$\left\{1-\left[\sum_{j=N}^{N+Q}\binom{N+Q}{j}\times\right.\right.$$
$$\left.\left.\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}}}\right)^{N+Q-j} e^{-\frac{\left(\xi^{-\left(1-\frac{L+1}{L}r\right)}\right)j}{0.5\gamma_{SR}}}\right]^{W}\right\}^{N-K} \tag{45}$$

one in the upper bound expression of eq.(35) and by the

$$P_{out}^{(i)}(R) = \left[\sum_{j=N+K}^{N+Q}\binom{N+Q}{j}\times\right.$$
$$\left.\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}}}\right)^{N+Q-j} e^{-\frac{\left(\xi^{-\left(1-\frac{L+1}{L}r\right)}\right)j}{0.5\gamma_{SR}}}\right]^{W} \tag{46}$$

one in the lower bound expression of eq.(36) respectively.

Let us now inspect the terms of eqs.(45)-(46) and identify their corresponding order of decay as $\xi \to \infty$. Therefore, we have

$$\lim_{\xi\to\infty} e^{-\frac{\left(\xi^{-\left(1-\frac{L+1}{L}r\right)}\right)j}{0.5\gamma_{SR}}} = 1 \tag{47}$$

and

$$\left(1-e^{-\frac{\xi^{-\left(1-\frac{L+1}{L}r\right)}}{0.5\gamma_{SR}}}\right)^{N+Q-j} \approx$$
$$\left(0.5\gamma_{SR}^2\right)^{-N+Q-j}\xi^{-(N+Q-j)\left(1-\frac{L+1}{L}r\right)} \tag{48}$$

Now having in mind that the outage probability of the system is dominated by the term having the largest exponent of ξ and using the results of eqs.(47)-(48) and (30) one can show that the term that dominates both the upper bound given by eq.(35) and the lower bound of eq.(36) is the

$$\binom{N}{K}\left(0.5\gamma_{SR}^2\right)^{-WQK}\xi^{-WQK\left(1-\frac{L+1}{L}r\right)}\times$$
$$\left(0.5\gamma_{SD}^2\right)^{-M}\xi^{-M\left(1-\frac{L+1}{L}r\right)}$$

one for $K = N-L+1$. Thus, using the definition of DMT eq.(20), we obtain the DMT curve of eq.(44) and that completes the proof. ■

VI. Numerical results and discussion

In this section representative simulations are provided in order to gain insight into the proposed technique's performance for different values of the involved parameters. To this end, the outage probability versus the transmit SNR of the corresponding techniques is depicted in the following figures for a transmission rate of $R = 1bit/s/Hz$ and source transmission power $P_S = 1$. Note that for a given target rate R, the target rate of the proposed cooperative scheme is set to $\frac{L+1}{L}R$ so that the comparison to the SIMO performance to be fair. We remind that this is due to the half duplex constraint which dictates that the proposed technique requires $L+1$ timeslots to transmit L symbols from the source to the destination.

More specifically, in Figure 2 the performance of the proposed technique is examined for different number of relay nodes $N = 5, 6, 7$ and 8. The destination node has $M = 2$ antennas, $L = 2$ and $\gamma_{SR}^2 = \gamma_{SD}^2 = 1$. As it is depicted, in low SNR regimes the proposed scheme achieves worse performance than the non-cooperative SIMO system. This is typical in half duplex cooperative techniques, and it is due to the certain spectrum utilization loss resulted by the half duplex constraint [4]. Contrariwise, for high SNR regimes, the benefits of diversity overtake the costs of the half duplex nature of the proposed scheme and the latter achieves better performance than the one of the non-cooperative system. An increase in the number of relays results in improved performance, as it is expected, and it is also proved by the theoretical analysis. In the same figure, the theoretical outage probability of the proposed technique derived in Theorem 1 is also plotted. As we can see the theoretical results coincide with the ones of the simulations. In Figure 3 the corresponding DMT curves are plotted for each one of the cases considered in the experimental set-up of Figure 2. As it is evident, the proposed technique achieves better diversity gain for the same multiplexing gain with an increase in the relays' number N.

In Figure 4 the performance of the technique is compared

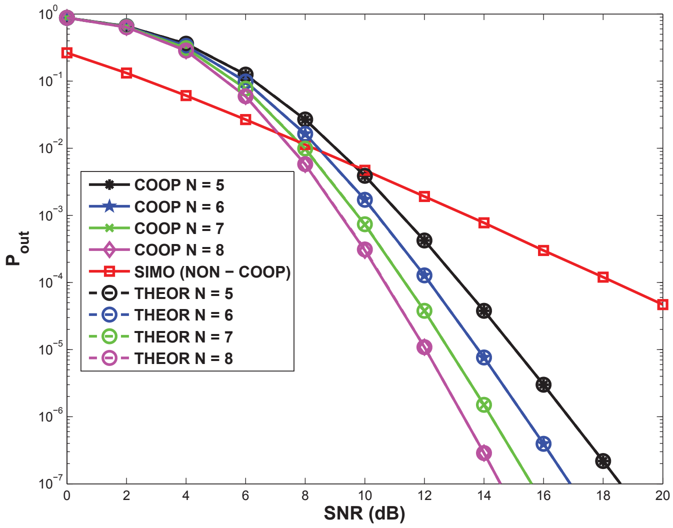

Fig. 2: Outage probability versus transmit SNR of the non-cooperative (SIMO) and the proposed cooperative technique for a different number of relay nodes N, $M = 2$, $L = 2$ and $\gamma_{SR}^2 = \gamma_{SD}^2 = 1$

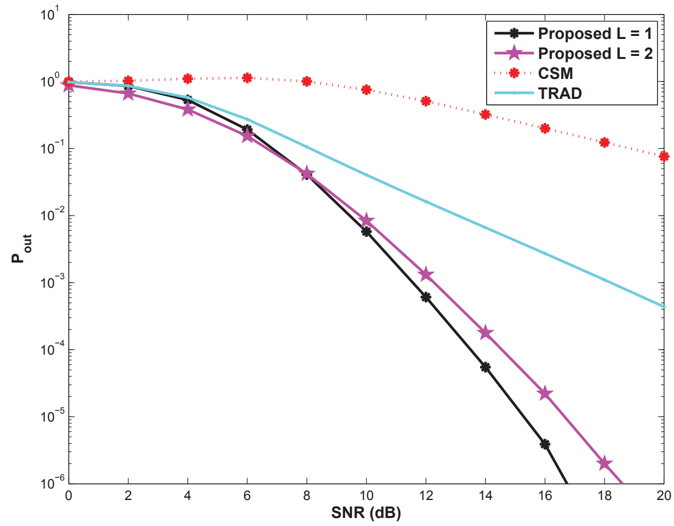

Fig. 4: Outage probability versus transmit SNR of the proposed cooperative technique for $L = 1$ and $L = 2$, the original DF technique of [4] and the CSM approach of [21] for $N = 4$, $M = 2$ and $\gamma_{SR}^2 = \gamma_{SD}^2 = 1$

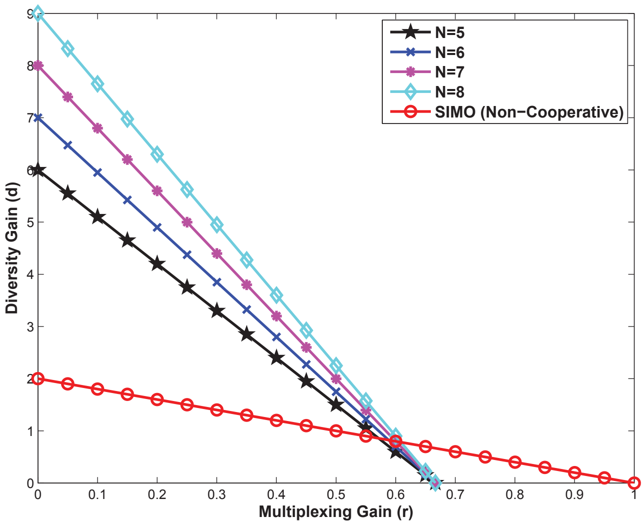

Fig. 3: DMT curves of the non-cooperative (SIMO) and the proposed cooperative technique for different value of relay nodes N, $M = 2$ and $L = 2$.

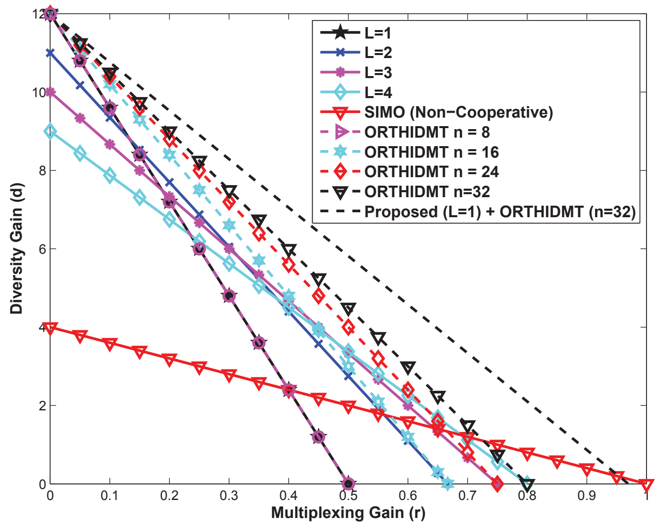

Fig. 5: DMT curves of the proposed cooperative technique for different values of L and the technique of [21] for $N = 8$, $M = 4$ and $\gamma_{SR}^2 = \gamma_{SD}^2 = 1$

to the ones of the original DF approach [4] and the CSM approach of [23]. We consider a destination of $M = 2$ antennas, $N = 4$ relays and $\gamma_{SR}^2 = \gamma_{SD}^2 = 1$. The performance of the proposed technique is depicted for $L = 1$ and $L = 2$. The original protocol of [4] was extended to the multi-antenna destination case. As it is evident from Figure 4, this technique achieves inferior performance to the proposed one's for both the values of L considered here. The CSM approach, can utilize only the two out of the four available relays, since according to the system description the number of the relays must be at most the number of the destination's antennas due to the fact that the $n-th$ relay forwards only the $n-th$ symbol (after a successful decoding). For a fair comparison we present a slight modification of the technique presented in [23] where we assume that each symbol is send to two relays so as to exploit all the four available relays and thus improving somewhat the performance of the technique. As it evident, the technique achieves a multiplexing gain of $2/3$, though the outage probability of the technique is much inferior to the one achieved by the proposed technique for the same multiplexing gain (for $L = 2$).

In Figure 5, the DMT curves of the proposed technique is compared to the ones of the technique of [21] and the ones of the hybrid approach that combines the proposed technique with the one of [21]. Note that in this figure we plot the DMT curves of the technique of [21] after it was cast to the multi-

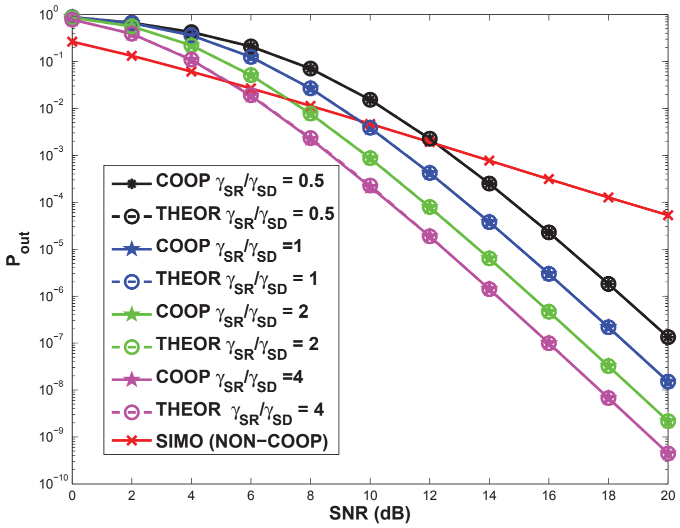

Fig. 6: Outage probability versus transmit SNR of the non-cooperative (MISO) and the proposed cooperative technique for different values of the ratio $\frac{\gamma^2_{SR_i}}{\gamma^2_{SD}}$ for $N = 5$, $M = 3$ and $L = 2$.

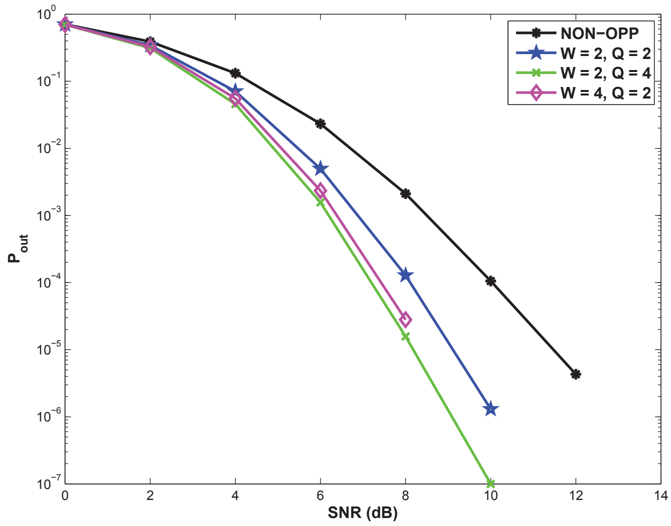

Fig. 7: Outage probability versus transmit SNR of the opportunistic extension of the cooperative technique for different values of W and Q for $N = 5$, $M = 3$ and $L = 2$.

antenna case for a fair comparison. Here we consider a system with $N = 8$ relays, $M = 4$ receiver antennas and $L = 1, 2, 3, 4$ respectively. For higher values of L the DMT curves show that the proposed technique exhibits increased multiplexing gain at the cost of diversity gain. Let us first note that the technique of [21] achieves a multiplexing gain of $n/(n+N)$, where n is the constellation length used by the technique. Thus we present the DMT curves of the latter technique for $n = 8, 16, 24, 32$ in order to achieve the same multiplexing gain with the one of the proposed technique for the considered values of L respectively. The DMT curve of [21] shows that the technique achieves a diversity gain independent of the constellation dimension n and a multiplexing gain of $n/(n+N)$. Nevertheless, according to the values of n we used here, the technique of [21] must employ constellations of high dimension n in order to achieve the same multiplexing gain with the one of the proposed approach resulting in significantly high decoding complexity. It is interesting to note that one may combine the proposed technique with the one of [21] to achieve improved performance. This can be done by applying the technique of [21] on each one of the parallel singular channels of the proposed technique. It can be shown (detailed derivation is not possible due to space limitations) that the resulting hybrid technique achieves a diversity gain of $M + N - L + 1$ and a multiplexing gain of $n/(n + 1)$. For example, we plot the DMT curve of this hybrid technique for $L = 1$ and $n = 32$. As it is evident the hybrid technique achieves the same diversity gain to the one of the proposed technique and the technique of [21], though it achieves significantly improved multiplexing gain. In Figure 6 we examine the impact of the ratio $\frac{\gamma^2_{SR}}{\gamma^2_{SD}}$ on the performance of the technique. The system has $M = 3$ destination antennas, $N = 5$ relays and $L = 2$ block size. We examine the performance for $\frac{\gamma^2_{SR}}{\gamma^2_{SD}} = 0.5, 1, 2$ and 4. In the same figure the performance of the corresponding SIMO system and the theoretical results of Theorem 1 are also depicted. It is evident, that as the source-relays channel exhibit better condition the performance is improved since it is the "weakest" part of the system that lacks of diversity. The latter observation designates also another advantage of the proposed technique. In cellular systems the users can employ the proposed technique with relays that are other users in their close proximity and therefore have channels in relative good condition, so as to improve the uplink performance when they share channels in relative bad condition with the corresponding base station.

Finally in Figure 7 we examine the performance of the opportunistic extension of the technique. A system with $M = 3$, $L = 2$ and $N = 5$ in considered and we plot the outage probability curves for the non opportunistic version, for the opportunistic version for $W = 2$ users and $Q = 2$ surplus relays, for $W = 4$ users and $Q = 2$ surplus relays and for $W = 2$ users and $Q = 4$ surplus relays respectively. As it is shown, even with a few number of users or surplus relays the opportunistic extension of the proposed technique presents severely improved outage probability.

VII. Conclusion

In this paper a new uplink transmission technique for a cooperative system consisted of a single-antenna source, single antenna relay nodes and a multi-antenna destination node has been proposed. The new scheme is based on the DF protocol and exploits the spatial degrees of freedom of the virtual MIMO channel consisted by the single antenna relays and the multi-antenna destination nodes so as to provide increased multiplexing gains compared to the original cooperative protocols that achieved a constant multiplexing gain of 1/2 while providing also cooperative diversity gain. The theoretical outage probability and the DMT curve of the proposed scheme was derived for Rayleigh fading channels. The technique achieves a multiplexing gain of $L/(L+1)$ and a diversity gain equal to $M+N-L+1$ where the symbol block size L can be used to trade off between the diversity and the multiplexing gain, according the application needs. The performance of the technique was evaluated by indicative simulations and compared to existing literature techniques. Then, the new technique was extended so as to exploit the opportunisms, that may be offered by multiple users and redundant relays existence. Novel simple user/relay selection criteria was derived and the performance of the resulting opportunistic scheme was evaluated theoretically by deriving an upper and a lower bound for its outage probability and the corresponding DMT curve. As it is shown, the opportunistic extension of the technique exhibits improved diversity gain equal to $WQ(M+N-L+1)$ for W users and Q surplus relays for the same multiplexing gain.

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