Opportunistic Relaying for Multi-Antenna Cooperative Decode-and-Forward Relay Networks

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Abstract—**In this paper, we investigate the relaying scheme for multi-antenna cooperative networks without channel state information at the transmitters. It is shown that the classic opportunistic relaying scheme, which allows only one relay node to forward the message, may lead to significant loss when it is extended to the corresponding multi-antenna relay scenarios. A generalized opportunistic relaying approach, which selects more transmit antennas distributed on multiple relay nodes to transmit data simultaneously, is proposed to maximize the network throughput via balancing the source-relay and the relay-destination channels. Numerical examples show the large impact of multiple antennas and relays on the network throughput, and the significant gains obtained through the proposed opportunistic cooperation scheme.**

I. Introduction and Related Work

Cooperative transmission, as an emerging technology to provide reliable high data rate services in dynamic environments, promises significant macro space diversity and coverage extension in wireless networks [1], [2]. In this framework, the system performance is often influenced by two major factors: the network configuration and the cooperative strategy.

One of the network configurations that have been explored extensively is the transmission from the source to the destination with the help of K relay nodes, and various kinds of cooperative strategies have been developed. Specifically, the relaying strategy, in which the relay nodes facilitate the transmission by decode-and-forward (DF), provides the possibility to vary the communication rate and prevent error propagation [2], [3].

Considering the network configurations with multiple-antenna nodes is a natural extension to the state of the art due to the significant improvements in terms of spectral efficiency and link reliability provided by the multiple input multiple output (MIMO) technique. In this scenario, several proposals have been developed under different channel state information (CSI) assumptions. If the relay nodes have perfect CSI about the source-relay (S-R) and relay-destination (R-D) channels, each relay can perform a gain matrix to process the S-R signal and preprocess the R-D signal to improve the end to end performance [4], [5]. In the absence of R-D knowledge at the relay nodes, the relay can at best exploit the multiplexing structure to transmit independent data stream, and the processing is performed at the destination [5].

In this paper, we propose the opportunistic relaying approach in the MIMO relay setting without CSI at the transmitters. Opportunistic relaying was originally suggested to provide better performance with a low cost and complexity implementation for single-antenna relay networks [6], in which the best relay node is selected to forward the information. Then, it is introduced into the multi-antenna relay networks [5], [7]. However, there are still several basic questions that are not answered when the system model extends to the MIMO relay networks. Is the method of the best relay selection for single-antenna relay networks still optimal? If not, are there any efficient algorithms to decide how many and which relays should be selected for the MIMO relay setting?

In this research, we investigate how opportunistic cooperation can help the forwarding of information in DF based wireless MIMO relay networks. In contrast with the conventional opportunistic selection, the proposed solution allows more transmit antennas distributed on multiple nodes to transmit the message simultaneously. To make the judicious selection among multiple transmit antenna candidates, the first step of the proposed approach is to evaluate different non-degraded S-R channels, which is realized via the majorization theory. Then, the selection algorithm is proposed to maximize the network throughput with reference to the CSI knowledge at the destination. The proposed technique can be utilized in various network configurations, and the simulations validate the effectiveness of our proposed approach.

Throughout this paper, we use boldface upper-case letters to denote matrices, boldface lower-case letters to denote column vectors, and italics to denote scalars. The superscripts $(\cdot)^H$ stand for conjugate transpose; $[\mathbf{A}]_{i,j}$ and $[\mathbf{A}]_{:,j}$ denote the $(i\text{th}, j\text{th})$ element and jth column of matrix $\mathbf{A}$, respectively; and $[\mathbf{c}]_i$ denotes the ith element of the vector $\mathbf{c}$. $\mathbf{I}_M$ denotes the $M \times M$ identity matrix; $\oplus_{i=1}^{n} \mathbf{A}_i$ denotes a block diagonal matrix with block elements given by $\mathbf{A}_i$; $\det(\mathbf{A})$ denotes the determinate; and $\text{diag}(\mathbf{A})$ denotes the main diagonal of the matrix $\mathbf{A}$. For a set $\mathcal{X}$, the operator $|\mathcal{X}|$ denotes the cardinality of the set. Likewise, all logarithms are to the base 2.

II. System Model

The two-hop MIMO relay network is illustrated in Fig. 1, where the source node (S) with N_s transmit antennas attempts to communicate to the destination node (D) with N_d receive antennas assisted by a number of relays. The size of the relay network, i.e., the total number of the helpers, is K, comprised of either cooperating users [1] or fixed relay stations [3]. The

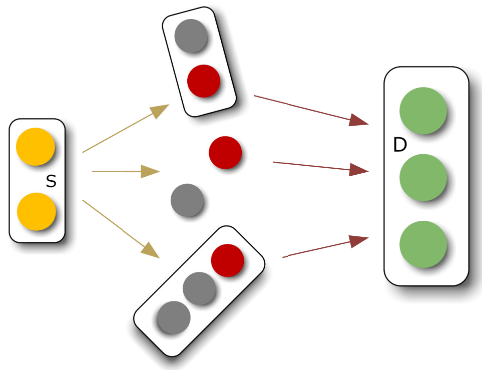

Fig. 1. System model of a dual-hop MIMO relay network. Some transmit antennas of the relays are allowed to forward the message while others keep silent.

number of the antennas at the relay j is denoted by N_j, where $j = 1, 2, \cdots, K$, and the total number of transmit antennas at the relays is $N_T = \sum_{j=1}^{K} N_j$. The direct link between the source and the destination is ignored due to the large distance and additional pathloss in comparison to the relay links in the practical deployment of the relays [5]. In addition, only TDD transmission protocols are taken into account in the sequel due to the half-duplex constraint of the practical hardware.

We model the S-R and R-D links as the quasi-static flat-fading channel, which is applicable to the scenarios of narrow-band transmissions in a low-mobility environment. We assume that the channel state information (CSI) is known at the receiver, but no CSI at the transmitter, i.e., the relay j has knowledge of the corresponding S-R link, and the destination can obtain full knowledge of both S-R and R-D channels[1]. Furthermore, the data transmission is over two time slots using two hops. In the first time slot, the source broadcasts the signal to all relay nodes (henceforth called S-R phase). Then, only N_L of the N_T transmit antennas are selected to forward the message in the second time slot (R-D phase)[2].

Without CSI at the source node, a reasonable strategy is to utilize uniform power allocation across the antennas at the source for the S-R phase. Then, the received signal at the relay j can be written as

$$\mathbf{r}_j = \sqrt{\frac{P_s}{N_s}} \mathbf{H}_j \mathbf{x}_s + \mathbf{n}_j, \; j = 1, 2, \cdots, K \qquad (1)$$

where $\mathbf{r}_j \in \mathbb{C}^{N_j \times 1}$ is the received signal vector; P_s denotes the total transmit power of the source node; $\mathbf{H}_j \in \mathbb{C}^{N_j \times N_s}$ is the channel matrix from the source node to the relay j; $\mathbf{x}_s \in \mathbb{C}^{N_s \times 1}$ is the transmitted signal vector; and $\mathbf{n}_j \in \mathbb{C}^{N_j \times 1}$ is the channel noise vector, assumed independent and identically distributed (i.i.d.) complex Gaussian with zero mean and unit variance $\sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{N_j}\right)$.

[1]In practice, the relays and the destination can learn the S-R and R-D links by training, respectively, and the CSI knowledge of the S-R links can be sent to the destination node.

[2]This is one of the main differences between the proposed scheme and the method of [5]. The later method assumes all the selected transmit antennas are from one and only one relay node.

Each relay node decodes their received signal independently, and the N_L selected transmit antennas forward the signal $\mathbf{x}_r \in \mathbb{C}^{N_L \times 1}$ to the destination simultaneously in the R-D phase. We place a limit on the total transmit power constraint P_r across the selected transmit antennas, which controls the power level at the receiver side. For a given realization of the channel, the optimal power allocation across the transmit antennas depends on the CSI knowledge about the cooperative networks at the relay nodes. Without CSI knowledge of the overall forward R-D channel $\mathbf{G}_T \in \mathbb{C}^{N_d \times N_T}$, the transmit antennas can at best use an identity transmit signal covariance matrix. Then, the signal received at the destination can be written as:

$$\mathbf{y} = \sqrt{\frac{P_r}{N_L}} \mathbf{G}_L \mathbf{x}_r + \mathbf{n}_d \qquad (2)$$

where the vector $\mathbf{y} \in \mathbb{C}^{N_d \times 1}$ is the received signal vector; $\mathbf{G}_L \in \mathbb{C}^{N_d \times N_L}$ is the channel matrix from N_L selected transmit antennas to the destination; and $\mathbf{n}_d \in \mathbb{C}^{N_d \times 1}$ is the Gaussian noise at the destination $\sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{N_d}\right)$.

Note that for a relay selection algorithm to be effectively implemented in practice, a low-rate feedback should be allowed from the destination to the relay nodes, which will be specifically stated when we introduce them later.

III. Relay Scheme and Relay Selection Algorithm

In the first hop, all the relays listen to the common information from the source and decode the message based on the channel realization $\mathbf{H}_j$. Intuitively, the better $\mathbf{H}_j$ represents the higher reliably-decoded information rate. However, in the MIMO multicast setting, the channel ranking is not straightforward, because the S-R channel is inherently non-degraded. In the sequel, we first introduce the approach that orders the S-R channels based on the majorization theory, which was suggested in [8] for MIMO broadcast channel. Then, we propose the relay selection algorithm to maximize the network throughput.

A. Relay Nodes Ordering Based on the Majorization Theory

With channel knowledge unknown to the transmitter, the V-BLAST structure, where the message at the source is multiplexed into N_s independent data streams, is used to extract the potential multiplexing gains from the S-R links. The relays that have transmit antennas selected for the R-D phase detect and decode the data streams through the MMSE-SIC structure, a combination of minimum mean square error estimation and successive interference cancellation, which consists of N_s iterations, each aimed at decoding one stream [9]. The Shannon capacity from the source to the relay j can be achieved by the detector if each stream is correctly decoded:

$$C_{s,j} = \log\det\left(\mathbf{I}_{N_s} + \frac{P_s}{N_s}\mathbf{H}_j^H \mathbf{H}_j\right), \; j = 1, 2, \cdots, K. \qquad (3)$$

When the channel between the source and each relay is degraded, e.g., SISO, SIMO and MISO, the relay nodes can be ordered according to the channel realization $\mathbf{H}_j$. That is, if the relay j decodes the message from the source, all the receivers that have larger capacity than $C_{s,j}$ will also decode the message. But for the MIMO channels, the ranking method is not straightforward, i.e., even if $C_{s,i}$ is larger than $C_{s,j}$, the message that node j can decode may not be decodable for node i. Therefore, it is difficult to evaluate the quality of different MIMO channel directly in the multicast setting.

The ranking by majorization theory was developed in [8] for MIMO broadcast channel. In this study, we introduce this approach as the preparation for the proposed relay selection algorithm. For convenient discussion, we consider the case of $N_s = K = 2$.

Let $\boldsymbol{\lambda}_j \in \mathbb{R}^{2\times 1}$, $j = 1, 2$, denotes the singular value sequence of $\mathbf{H}_j^H \mathbf{H}_j$; $\mathbf{u}_j \in \mathbb{R}^{2\times 1}$, $j = 1, 2$, is a function of sequence $\boldsymbol{\lambda}_j$, where $[\mathbf{u}_j]_1$ and $[\mathbf{u}_j]_2$ are associated with the minimal singular value $\lambda_{(1)}$ and the sum of the singular value $\lambda_{(1)} + \lambda_{(2)}$ of the relay j, respectively. Then, we order the different MIMO channel, $\mathbf{H}_1$ and $\mathbf{H}_2$, via sorting the rows of the matrix $[\mathbf{u}_1\, \mathbf{u}_2]^T$, in ascending order (by the *sortrow* function in Matlab). According to the majorization theory (see [8], [10] for further references), all streams decodable for channel $\mathbf{H}_1$will be decodable for channel $\mathbf{H}_2$ if

$$[\mathbf{u}_1]_1 \leq [\mathbf{u}_2]_1 , [\mathbf{u}_1]_2 \leq [\mathbf{u}_2]_2 . \tag{4}$$

Due to the inherently non-degraded property, the condition (4) does not always hold for MIMO relay channel. If that happens, e.g., $[\mathbf{u}_1]_1 \leq [\mathbf{u}_2]_1$ and $[\mathbf{u}_1]_2 > [\mathbf{u}_2]_2$, we fix the value of $[\mathbf{u}_1]_2$ to $[\mathbf{u}_2]_2$ to keep the condition (4) to hold. In this way, we can order the non-degraded MIMO relay channel, and evaluate the quality of different relay nodes in the MIMO multicast setting.

We should note that when the channel from the source to the relay j is SISO, SIMO or MISO, the majorization condition (4) is always met, because there is only one singular value and the ranking can always be performed. It has been proved that the selection algorithm (discussed later in Sec. III-C) based on the relay ordering is optimal for these degraded channels (the detail will be discussed in the journal version paper). For the non-degraded S-R links, the ordering through majorization theory may not maintain optimality, which is also pointed out in MIMO broadcast channel [8].

B. The Proposed Relaying Protocol

Let $\mathbf{c}$ be the $N_T \times 1$ vector, denoting the S-R capacity for every transmit antenna of the multiple relays

$$\mathbf{c} = \text{diag}\left(\oplus_{j=K}^{1}\left(C_{s,j}\mathbf{I}_{N_j}\right)\right) \tag{5}$$

where the vector length is N_T; and each element $[\mathbf{c}]_i$ denotes the capacity from the source to the relay possessing the corresponding transmit antenna. Every N_j elements have the same value $C_{s,j}$, and the elements are in the descending order.

If a transmit antenna subset $\mathcal{R}$, $|\mathcal{R}| = N_L$, is selected to forward the message, the corresponding relays carrying the transmit antennas in that set have to decode the signals correctly. Thus, the capacity of the S-R link is

$$C_{s,r}(\mathcal{R}) = \min_{i\in\mathcal{R}}\left([\mathbf{c}]_i\right). \tag{6}$$

In the second time slot, a virtual V-BLAST structure is considered, in which several selected transmit antennas forward the uncorrelated and independently encoded substreams[3]. The encoding can be realized via the parallel channel coding [11] or rateless coding with different random generator seeds at each relay (see [3], [12], [13] and references therein), and the multiple antennas at the destination are used to decode the different substreams. The Shannon capacity from the selected transmit antennas to the destination is given by

$$C_{r,d}(\mathcal{R}) = \log\det\left(\mathbf{I}_{N_d} + \frac{P_r}{|\mathcal{R}|}\mathbf{G}_L\mathbf{G}_L^H\right) \tag{7}$$

which can be approached with MMSE-SIC detector [9], or the strategy of rateless coding with acknowledgment [12].

The capacity for this two-hop relay scheme with the transmit antenna set $\mathcal{R}$ can be observed as:

$$C_{srd}(\mathcal{R}) = \frac{1}{2}\min\left(C_{s,r}(\mathcal{R}), C_{r,d}(\mathcal{R})\right) \tag{8}$$

where the factor $1/2$ penalty stands for the half multiplexing loss. Thus, the network throughput is defined as:

$$C = \max_{\mathcal{R}} C_{srd}(\mathcal{R}). \tag{9}$$

There exists a fundamental *tradeoff* between the S-R and the R-D links. In general, the optimal solution of maximizing $C_{s,r}$ leads to bad performance to increase MIMO capacity $C_{r,d}$ and vice versa. In the next subsection, we will propose an efficient relay selection algorithm to maximize the network throughput in (9).

C. Relay Selection Algorithm

Intuitively speaking, if the minimal $C_{s,j}$ is even larger than the maximal $C_{r,d}$ for all possible selection set, the relay selection problem in (9) will be simplified into an antenna selection problem of MIMO systems

$$C_{AS} = \max_{\mathcal{R}} C_{r,d} \tag{10}$$

where $\mathcal{R}$ denotes the selected transmit antenna set. From this point of view, we can conclude that the antenna selection is a specific case of the relay selection problem considered in this study. In other words, the problem of relay selection is much harder than that of the antenna selection.

However, a simple exact solution to antenna selection does not exist. The only known exact solution is by exhaustive search, which is time consuming [14]. Therefore, several approximate algorithms have been investigated [15], which achieve very close performance to that of the exact selection procedure. Without loss of generality, we denote the antenna selection schemes as *AntSel*, which will be called as a sub-routine to develop our relay selection algorithm.

In order to make the relay node selection, instead of computing the capacity for $\binom{N_T}{N_L}$ possible combinations of selected N_L relays (as in the exhaustive search), the proposed algorithm starts with the ordered relay nodes (See Sec. III-A) and selects the N_L transmit antennas from a decreasing subset

[3]In here, the virtual V-BLAST means the transmit antennas are not collocated as the traditional structure [9].

to maximize $C_{r,d}$ per step. According to this motivation, we propose the relay selection algorithm as follows:

Algorithm 1 MIMO Relay Selection Algorithm

1) Initialization:
   $i = 1$, $\mathcal{V}_i = \{1, 2, \cdots, N_T\}$;
   arrange the $C_{s,j}$, $j = 1, \cdots, K$, in ascending order according to Sec. III-A; and $\mathbf{c} = \text{diag}\left(\oplus_{j=K}^{1}\left(C_{s,j}\mathbf{I}_{N_j}\right)\right)$.
2) For different selected transmit antenna number l, in each step i, select relay subset $\mathcal{R}^{(i)}$ as
$$\left(C_{r,d}^{(i)}, \mathcal{R}^{(i)}\right) = \text{AntSel}\left(P_r, N_d, \mathbf{G}_T, \mathcal{V}_i, l\right). \quad (11)$$
   $n = \arg\min_{k\in\mathcal{R}^{(i)}} [\mathbf{c}]_k$, $C_{s,r}^{(i)} = [\mathbf{c}]_n$, $i = i + 1$, and $\mathcal{V}_i = \{1, 2, \cdots, n-1\}$.
3) If $\mathcal{V}_i = \{1, 2, \cdots, l-1\}$,
   calculate $C_i = \frac{1}{2}\min\left(C_{s,r}^{(i)}, C_{r,d}^{(i)}\right)$ and $J_l = \arg\max_i C_i$. The relay set and the network throughput for the l selected transmit antennas is $\mathcal{R}_l = \mathcal{R}^{(J_l)}$ and $C_l = C_{J_l}$, respectively.
   if $l = N_T$, go to step 4, else, go to step 2.
4) Calculate $J = \arg\max_l C_l$. The optimal relay set and the network throughput are $\mathcal{R} = \mathcal{R}_J$ and $C = C_J$, respectively.

There are several important aspects we should note. First, for a certain N_L, a simple exact solution to transmit antenna selection involves an exhaustive search over all possible $\binom{N_T}{N_L}$ transmit antenna set, which grows exponentially with N_T for $N_L \approx N_T/2$. However, our proposed algorithm solves this selection by calling antenna selection subroutine $AntSel$ for less than N_T times. Several schemes have been shown that an $\mathcal{O}(N_T^3)$ complexity approximate procedure $AntSel$ exists, providing performance very close to that of exact selection [15]. As a consequence, the proposed scheme can be expected to have $\mathcal{O}(N_T^4)$ complexity for practical purposes.

Second, the optimal number of selected relays N_L can also be found, if additional computing complexity is paid. The most intuitive method is to find the network throughput let $N_L = 1$ to N_T, as Algorithm 1 shown. In this way, the problem of how many and which relay nodes should be selected can be solved at the same time, expecting to have less than $\mathcal{O}(N_T^5)$ complexity comparing to the complexity $\sum_{N_L=1}^{N_T}\binom{N_T}{N_L} = 2^{N_T} - 1$ of the exact search.

Furthermore, the selection algorithm is executed at the destination, which has the full CSI knowledge of the S-R and R-D channels. After the calculation, the optimal transmit antenna set $\mathcal{R}$ will be transmitted via a feedback channel. Specifically, if there are N_T transmit antennas in the network, at most N_T bits are needed to identify all the different selection results.

IV. Numerical Results

Computer simulations are carried out to validate the performance of the proposed algorithm. For the sake of completeness, in all the figures, we also show the performance corresponding to the case of optimal selection routing (OSR) of [5], R-D link based relay selection (without S-R knowledge at the destination) and no advanced selection strategy (relay nodes are chosen at random). The cooperative system with N_s antennas at the source, N_d antennas at the destination and K relays is called as a $N_s \times K \times N_d$ network in the sequel.

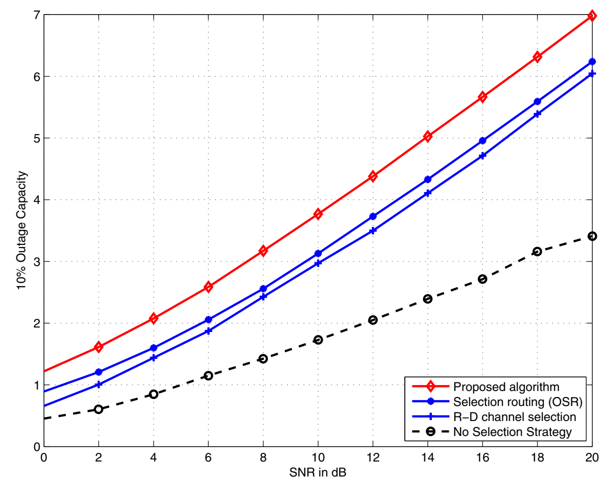

Fig. 2. Outage capacity versus the SNR for the $2\times4\times2$ MIMO relay network with a random number of transmit antennas between 1 and 8 equipped at each relay node.

Through our simulations, we assume that the total transmit power for the source and the relays is the same $P_s = P_r = P$. The selected performance metric is the outage capacities [9] with the outage rate of 10%, which are obtained by averaging over 10,000 channel realizations. The fast antenna selection technique [15] is used as the subroutine $AntSel$ in (11), which has $\mathcal{O}(N_T^3)$ complexity and provides performance very close to that of exact selection.

Considering the $2 \times 4 \times 2$ MIMO relay network with a random number of antennas at each relay node, Fig. 2 plots the outage capacity versus the average SNR for different relay selection strategies. This figure shows the advantage of the proposed algorithm over the existing methods. For the cases that multiple antennas are equipped at each terminal, the proposed algorithm attempts to select more useful transmit antennas to forward the message, while the OSR chooses all the transmit antennas of one best relay node. Therefore, the performance gains come from the more efficient use of the power. Furthermore, without S-R knowledge at the destination, the selection method based on R-D channel is a good choice to improve the network throughput compared with the case of no selection strategy is used.

It is illustrated that how the outage capacity depends on the antenna number at the destination N_d in Fig. 3. As shown, there is a noticeable gain in the outage capacity for increasing the receive antennas at the destination, but this trend is more prominent for low N_d, and almost no additional improvement is achieved for $N_d > 4$. This is because increasing the number of the antennas at the destination can only improve the performance of the R-D channel. When the antenna number

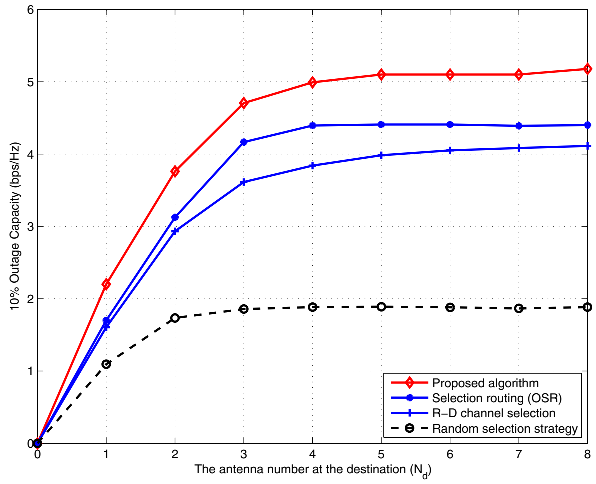

Fig. 3. Outage capacity versus the antenna number at the destination for the $2 \times 4 \times N_d$ MIMO relay network with a random number of transmit antennas between 1 and 8 equipped at each relay node. $P = 10$ dB.

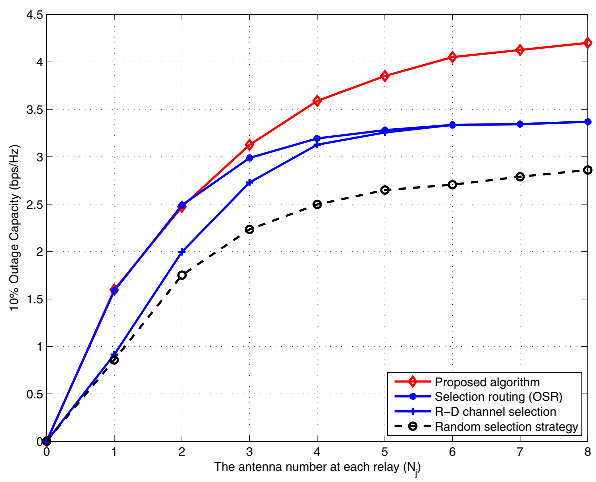

Fig. 4. Outage capacity versus for the antenna number at each relay for the $2 \times 4 \times 2$ MIMO relay network. Each relay is equipped with the same number of transmit antennas N_j from 1 to 8; the transmit power is $P = 10$ dB.

at the source is fixed to $N_s = 2$, the overall link quality is dominated by the S-R channel.

The outage capacity versus the antenna number at each relay N_j is shown in Fig. 4 for the $2 \times 4 \times 2$ MIMO relay network, in which each relay is equipped with the same number of antennas. The outage capacity achieved by the method of [5] is very close to the proposed scheme at low N_j, and practically merged with R-D based selection at high N_j. The reason for such performance is that the power gains provided by the proposed scheme is more evident for higher N_j, while the OSR method equally splits the power at multiple transmit antennas of a certain relay node. When the number of the antennas at the destination is fixed, the OSR fails to provide more power gain as N_j increases, and the overall performance is limited by the R-D channel. However, the achieved gains by the proposed scheme become more substantial at high N_j.

V. Conclusion

In this paper, we have studied opportunistic relaying for dual-hop wireless MIMO relay networks. We extended the recent optimal relaying scheme, opportunistic relaying, to the MIMO relay scenarios. In contrast with the conventional selection, where the best relay node is selected to forward the message, the proposed solution allows more transmit antennas distributed on multiple relays to transmit data simultaneously. To make the judicious selection among transmit antenna candidates in the network, the proposed scheme attempts to balance the S-R and the R-D channels to maximize the network throughput according to the S-R links ordering, which is motivated by the majorization theory. Numerical examples have shown the large impact of multiple antennas and relays on the network throughput, and significant gains have been obtained compared to the conventional counterpart.

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