

A NEW APPROACH FOR HIGH DATA RATE RELAY TRANSMISSIONS USING MULTIPLE ANTENNAS

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ABSTRACT

Herein, we present a novel approach for high data rate transmission in a wireless relay network. The system include a source, a destination and multiple relays. All nodes are equipped with multiple antennas. A half-duplex transmission protocol and a decode-forward transmission mode are deployed in the system. Our approach splits the data at the source into multiple independent data streams, and send them to the destination via some selected relays at the same time. The relays are selected using an opportunistic approach based on spatially decomposing the channels and accessing the best modes. Simulation results show the benefits of our technique, particularly with correlated channels.

I INTRODUCTION

Wireless relay networks have attracted much attention recently, since they can provide better coverage and/or higher network throughput, and hence improve the overall system performance [1]. When multiple relays are available, they can be further exploited to obtain macroscopic diversity, multiplexing gain. Therefore, they can be utilized to further combat fading and improve coverage, link quality and system capacity.

Different relay protocols have been studied widely to improve the spectrum efficiency and system performance. These relay protocols are designed mainly for the amplify-forward (AF) and the decode-forward (DF) relay systems. The relays are often assumed to be half-duplex [2], since full-duplex relays are often difficult and expensive to be implemented. This, however, generates a pre-log factor $\frac{1}{2}$ for the overall system throughput and is therefore not very spectral efficient. More spectral efficient protocols are proposed recently by using e.g. two half-duplex relays at the same time [3, 4].

When antenna arrays are deployed in the wireless system, they can be used to exploit the spatial multiplexing, diversity and array gains. The conventional spatial-temporal transmission schemes have been extended to the MIMO cooperative systems. In [5], protocols have been designed to use the space-time codes in the cooperative wireless networks. The spatial multiplexing techniques have also been proposed to be used in distributed MIMO systems [6].

In this paper, we present a novel approach for high data throughput relay transmissions with multiple relays equipped with multiple antennas. The basic idea is to send multiple independent spatial data streams to different relays and then to collect them at the destination. The relays are selected using an opportunistic approach: an available spatial mode is allocated to a given relay only if it involves a sum-rate improvement. Due to this "relay diversity" effect, the overall throughput grows as a

function of the number of candidate relays. We implement this idea by spatially decomposing the channels and by accessing the single modes with a technique previously proposed for multiuser MIMO downlink transmissions [7] and here extended to multi-antenna relay transmissions.

This paper is organized as follows. In Section II, we briefly describe the system model along with the transmission protocol that are used in our study. We then break the relay system into two phases, namely the downlink phase and the uplink phase, and present our algorithm in Section III and Section IV respectively. Section V describes the joint downlink and uplink algorithm that connects the downlink phase and uplink phase together. In Section VI, simulation results are presented showing the gain of our algorithm. Finally, we conclude in Section VII,

II SYSTEM MODEL

We consider a system with one source (S), one destination (D) and r relays (R). Each relay uses a decode-forward policy. Moreover each node is equipped with multiple antennas; more specifically N_s , N_d and N_r antennas are deployed respectively at the source, at the destination and at each of the r relays. We assume an infinite buffer at the source side.

The transmission can be divided in two phases. During the first phase (*downlink phase*) the source transmits to a set $\Phi \subseteq \{R_1, \dots, R_r, D\}$ of nodes. During the second phase (*uplink phase*) a second set $\Omega \subseteq \{\Phi \setminus D\} \cup S$ of nodes transmits to the destination. In the following we give some examples for a system with one source (S), two relays (R_1, R_2) and one destination (D) each with $N_s = N_d = N_r = N$ antennas.

- $\Phi = \{D\}$ and $\Omega = \{S\}$. The proposed scheme is equivalent to a MIMO single user transmission between source and destination. Up to N spatial streams are available for transmission.
- $\Phi = \{R_1, R_2\}$ and $\Omega = \{R_1, R_2\}$. During the downlink phase, up to N spatial streams are divided between R_1 and R_2 . During the uplink phase R_1 and R_2 transmit up to N independent streams to the destination.
- $\Phi = \{R_1, D\}$ and $\Omega = \{R_1, S\}$. During the downlink phase, up to N spatial streams are divided between R_1 and D . During the uplink phase R_1 and S transmit independent streams to the destination.

The transmission protocol is summarized in Table 1.

We represent the channel response between each couple of transmit/receive antennas as a complex coefficient, in order to model the frequency response of a given carrier in an OFDM system. We indicate by \mathbf{H}_{SR_i} , $i = 1, \dots, r$ the $N_R \times N_S$

Time slot 1 (downlink phase)	Time slot 2 (uplink phase)
$S \rightarrow \Phi$	$\Omega \rightarrow D$

Table 1: Transmission protocol.

channel matrix between the source and the i th relay and by $\mathbf{H}_{R_i D}$, $i = 1, \dots, r$ by $N_D \times N_R$ the channel matrix between the i th relay and the destination.

The transmission protocol described in Table 1 can be equivalently modelled by introducing two *virtual relays*. More specifically the link between the source and the first virtual relay (indicated with the index $r+1$) models the direct link between source and destination during the downlink phase. The link between the second virtual relay (indicated with the index $r+2$) and the destination models the direct link between source and destination during the uplink phase.

Let \mathbf{H}_{SD} the $N_D \times N_S$ channel matrix between source and destination; the channel matrices associated to the virtual relay $r+1$ are defined as follows

$$\mathbf{H}_{SR_{r+1}} = \mathbf{H}_{SD} \quad \mathbf{H}_{R_{r+1}D} = \mathbf{0} \quad (1)$$

where $\mathbf{0}$ denotes the null matrix. The channel matrices associated to the virtual relay $r+2$ are defined as

$$\mathbf{H}_{SR_{r+2}} = \mathbf{0} \quad \mathbf{H}_{R_{r+2}D} = \mathbf{H}_{SD} \quad (2)$$

Keeping in mind the definitions introduced in (1) and (2), in this document we will refer to a system with $r+2$ relays without differentiating (unless differently specified) between relays and virtual relays. In the same way Φ and Ω will refer to a given set of nodes in the original setup with direct connection between source and destination or to the associated set of nodes in the equivalent setup using virtual relays. The equivalence between original system with direct link between source and relays and equivalent system, where the direct link is modeled by means of two virtual relays, is showed in Figure 1.

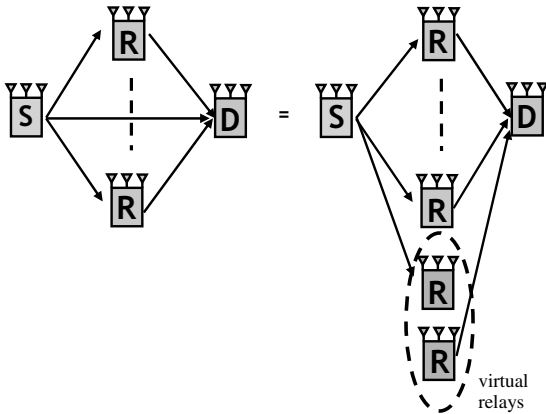


Figure 1: Equivalence between original system with direct link between source and relays and equivalent system, where the direct link is modeled by means of two virtual relays.

III DOWNLINK PHASE

The received signal at the j th relay during the downlink phase can be written as

$$\mathbf{y}_{R_j} = \mathbf{H}_{SR_j} \mathbf{x}_S + \mathbf{n}_{SR_j}, \quad j \in \Phi \quad (3)$$

\mathbf{x}_S is the $N_S \times 1$ signal vector transmitted by the source, and \mathbf{n}_{SR_j} is the vector of i.i.d. complex additive white Gaussian noise samples. The transmit signal is subject to the following sum power constraint

$$\mathbb{E} [\text{tr} [\mathbf{x}_S \mathbf{x}_S^H]] \leq P. \quad (4)$$

and can be written as

$$\mathbf{x}_S = \sum_{j \in \Phi} \mathbf{G}_j \mathbf{d}_{SR_j} \quad (5)$$

where \mathbf{G}_j is the $N_S \times |\mathcal{E}_j|$ complex precoding matrix associated to the j th active relay, \mathbf{d}_{SR_j} is the $|\mathcal{E}_j| \times 1$ data symbol vector sent to the j th active relay, and \mathcal{E}_j is the set of eigenmodes (or spatial dimensions) allocated to the j th active relay. In the remaining of this section we will recall the multiuser eigenmode transmission scheme (MET), proposed in [7] for a multi-input multi-output (MIMO) broadcast channel (BC).

The channel between source and the j th relay can be decomposed using the singular value decomposition (SVD) as $\mathbf{H}_{SR_j} = \mathbf{U}_{SR_j} \mathbf{\Sigma}_{SR_j} \mathbf{V}_{SR_j}^H$, where the eigenvalues in $\mathbf{\Sigma}_{SR_j}$ are arranged so that the ones associated with the allocated set \mathcal{E}_j appear in the leftmost columns. We denote these eigenvalues as $\Sigma_{SR_j,1}, \dots, \Sigma_{SR_j,|\mathcal{E}_j|}$. The j th node's receiver is a linear detector given by the Hermitian transposition of the leftmost $|\mathcal{E}_j|$ columns of \mathbf{U}_{SR_j} which we denote as $\mathbf{u}_{SR_j,1} \dots \mathbf{u}_{SR_j,|\mathcal{E}_j|}$. Likewise, we denote the leftmost $|\mathcal{E}_j|$ columns of the right eigenvector matrix \mathbf{V}_{SR_j} as $\mathbf{v}_{SR_j,1} \dots \mathbf{v}_{SR_j,|\mathcal{E}_j|}$. The signal after the detector can be written as

$$\begin{aligned} \mathbf{r}_{SR_j} &= [\mathbf{u}_{SR_j,1} \dots \mathbf{u}_{SR_j,|\mathcal{E}_j|}]^H \mathbf{y}_{SR_j} \\ &= \mathbf{\Gamma}_{SR_j} \mathbf{G}_j \mathbf{d}_{SR_j} + \mathbf{\Gamma}_{SR_j} \sum_{i \in \Phi, i \neq j} \mathbf{G}_i \mathbf{d}_i + \mathbf{n}'_j \end{aligned} \quad (6)$$

where \mathbf{y}_{SR_j} is the received signal at the j th node, \mathbf{n}'_j is the processed noise, and $\mathbf{\Gamma}_{SR_j} = [\Sigma_{SR_j,1} \mathbf{v}_{SR_j,1} \dots \Sigma_{SR_j,|\mathcal{E}_j|} \mathbf{v}_{SR_j,|\mathcal{E}_j|}]^H$ is a $|\mathcal{E}_j| \times N_S$ matrix. By defining the $\sum_{i \in \Phi, i \neq j} |\mathcal{E}_i| \times N_S$ matrix $\tilde{\mathbf{H}}_{SR_j}$

$$\tilde{\mathbf{H}}_{SR_j} = [\mathbf{\Gamma}_{SR_1}^H, \dots, \mathbf{\Gamma}_{SR_{j-1}}^H, \mathbf{\Gamma}_{SR_{j+1}}^H, \dots, \mathbf{\Gamma}_{SR_{|\Phi|}}^H]^H, \quad (8)$$

our zero-forcing constraint requires that \mathbf{G}_j lies in the null space of $\tilde{\mathbf{H}}_{SR_j}$. Hence \mathbf{G}_j can be found by considering the SVD of $\tilde{\mathbf{H}}_{SR_j}$:

$$\tilde{\mathbf{H}}_{SR_j} = \tilde{\mathbf{U}}_{SR_j} \tilde{\mathbf{\Sigma}}_{SR_j} [\tilde{\mathbf{V}}_{SR_j}^{(1)} \tilde{\mathbf{V}}_{SR_j}^{(0)}]^H, \quad (9)$$

where $\tilde{\mathbf{V}}_{SR_j}^{(0)}$ corresponds to the right eigenvectors associated with the null modes. The j th relay's precoder matrix is given by $\mathbf{G}_j = \tilde{\mathbf{V}}_{SR_j}^{(0)} \mathbf{C}_j$, where \mathbf{C}_j is determined later. Note that since $\tilde{\mathbf{H}}_{SR_j} \tilde{\mathbf{V}}_{SR_j}^{(0)} = \mathbf{0}$ for all $j \in \Phi$, it follows that $\mathbf{\Gamma}_{SR_j} \mathbf{G}_i = \mathbf{\Gamma}_{SR_j} \tilde{\mathbf{V}}_{SR_i}^{(0)} \mathbf{C}_i = \mathbf{0}$ for $i \neq j$ and any choice of \mathbf{C}_i . Therefore from (7), the received signal for the j th relay after combining contains no interference:

$$\mathbf{r}_{SR_j} = \mathbf{\Gamma}_{SR_j} \mathbf{G}_j \mathbf{d}_{SR_j} + \mathbf{n}'_j \quad (10)$$

We perform an SVD

$$\mathbf{\Gamma}_{SR_j} \tilde{\mathbf{V}}_{SR_j}^{(0)} = \bar{\mathbf{U}}_{SR_j} [\bar{\Sigma}_{SR_j} \mathbf{0}] \left[\bar{\mathbf{V}}_{SR_j}^{(1)} \bar{\mathbf{V}}_{SR_j}^{(0)} \right]^H, \quad (11)$$

where $\bar{\Sigma}_{SR_j}$ is the $|\mathcal{E}_j| \times |\mathcal{E}_j|$ diagonal matrix of eigenvalues, and assign $\mathbf{C}_j = \bar{\mathbf{V}}_{SR_j}^{(1)}$. From (10), the resulting rate for the j th node is

$$\sum_{k \in \mathcal{E}_j} \log \left(1 + \bar{\sigma}_k^{(j)^2} w_k^{(j)} \right), \quad (12)$$

where $\bar{\sigma}_k^{(j)^2}$ is the k th diagonal element of $\bar{\Sigma}_{SR_j}^2$ ($k \in \mathcal{E}_j$), \mathbf{W}_j is the $\mathcal{E}_j \times \mathcal{E}_j$ diagonal matrix of powers allocated to the eigenmodes, and $w_k^{(j)}$ is the k th diagonal element. Therefore the total transmitted power for this user is $\text{tr} [\mathbf{G}_j \mathbf{W}_j \mathbf{G}_j^H] = \text{tr} \mathbf{W}_j$. Let T be a given selection of users Φ and eigenmodes E_k ($j \in \Phi$), the power allocation problem for maximizing the sum rate given T can be found by using a waterfilling power allocation. We refer to [7] for the details.

IV UPLINK PHASE

The received signal at the destination during the uplink phase can be written as

$$\mathbf{y}_D = \sum_{j \in \Omega} \mathbf{H}_{R_j D} \mathbf{x}_{R_j} + \mathbf{n}_D \quad (13)$$

where \mathbf{x}_{R_j} is the $N_R \times 1$ vector transmitted by the i th relay whereas \mathbf{n}_D is the vector of i.i.d. complex additive white Gaussian noise samples $\mathbf{n}_D \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$. We consider two types of power constraints

1. Power constraint on the sum of the power transmitted by the different relays

$$\sum_{j \in \Omega} E \left[\|\mathbf{x}_{R_j}\|_2^2 \right] \leq P \quad (14)$$

2. Separated power constraints at each relay

$$E \left[\|\mathbf{x}_{R_j}\|_2^2 \right] \leq P, \quad j \in \Omega. \quad (15)$$

The first approach is more suitable for network of battery-powered nodes where a low energy consumption is required. The second type of power constraint is more suitable where the nodes are attached to a fixed power supply and the goal is the maximization of the throughput. In the remaining of this section we will extend the idea of the spatial decomposition described for the downlink in the previous section to an uplink transmission. The signal transmitted at the j th relay can be written as

$$\mathbf{x}_{R_j} = \mathbf{F}_j \mathbf{d}_{R_j} \quad (16)$$

where \mathbf{F}_j is the $N_R \times |\mathcal{I}_j|$ precoding matrix used at the j th active relay, whereas \mathbf{d}_{R_j} is the $|\mathcal{I}_j| \times 1$ data symbol vector transmitted from the j th relay and $|\mathcal{I}_j|$ is the set of eigenmodes allocated to the j th active node during the uplink phase.

Equivalently to the downlink case, we decompose each matrix $\mathbf{H}_{R_j D}$, $j \in \Omega$ by using an SVD

$$\mathbf{H}_{R_j D} = \mathbf{U}_{R_j D} \Sigma_{R_j D} \mathbf{V}_{R_j D}^H. \quad (17)$$

Also in this case the eigenvalues in $\Sigma_{R_j D}$ are arranged so that the ones associated to the set of allocated modes \mathcal{I}_j appear in the leftmost columns. These eigenmodes are denoted as $\Sigma_{R_j D, 1}, \dots, \Sigma_{R_j D, |\mathcal{I}_j|}$.

Differently from the previous case, where the set of active eigenmodes for a given link was selected at the receiver side by using a linear detector, in this case each relay selects the set of active modes at the transmit side by properly designing \mathbf{F}_j

$$\mathbf{F}_j = [\mathbf{v}_{R_j D, 1}, \dots, \mathbf{v}_{R_j D, |\mathcal{I}_j|}] \mathbf{C}_j \quad (18)$$

where $\mathbf{v}_{R_j D, i}$ is the right eigenvector associated to the i th selected eigenmode, and \mathbf{C}_j is a matrix that will be determined later.

The signal received at the destination (16) can be rewritten as

$$\mathbf{y}_D = \sum_{j \in \Omega} \mathbf{H}_{R_j D} \mathbf{F}_j \mathbf{C}_j \mathbf{d}_{R_j} + \mathbf{n}_D \quad (19)$$

$$= \sum_{j \in \Omega} \mathbf{\Gamma}_{R_j D} \mathbf{C}_j \mathbf{d}_{R_j} + \mathbf{n}_D \quad (20)$$

$$(21)$$

where $\mathbf{\Gamma}_{R_j D} = [\Sigma_{R_j D, 1} \mathbf{u}_{R_j D, 1}, \dots, \Sigma_{R_j D, |\mathcal{I}_j|} \mathbf{u}_{R_j D, |\mathcal{I}_j|}]$ is a $N_D \times |\mathcal{I}_j|$ matrix. By defining the $N_D \times \sum_{i \in \Omega, i \neq j} |\mathcal{I}_i|$ matrix

$$\begin{aligned} \tilde{\mathbf{H}}_{R_j D} &= [\mathbf{\Gamma}_{R_1 D}, \dots, \mathbf{\Gamma}_{R_{j-1} D}, \mathbf{\Gamma}_{R_{j+1} D}, \dots, \mathbf{\Gamma}_{R_{|\Omega|} D}] \\ &= [\tilde{\mathbf{U}}_{R_j D}^{(1)} \tilde{\mathbf{U}}_{R_j D}^{(0)}] \tilde{\Sigma}_{R_j D} \tilde{\mathbf{V}}_{R_j D}^H \end{aligned} \quad (22)$$

$$(23)$$

the combining matrix used at the destination to detect the signal of the j th relays is designed as follows

$$\mathbf{L}_j = \mathbf{D}_j \tilde{\mathbf{U}}_{R_j D}^{(0)H} \quad (24)$$

where \mathbf{D}_j will be determined later. Note that $\tilde{\mathbf{U}}_{R_j D}^{(0)H} \tilde{\mathbf{H}}_{R_j D} = \mathbf{0}$ for all $j \in \Omega$, and it follows that the received signal after the combining matrix associated with the j th relay can be written as

$$\mathbf{r}_{R_j D} = \mathbf{L}_j \mathbf{y}_D = \mathbf{D}_j \tilde{\mathbf{U}}_{R_j D}^{(0)H} \mathbf{\Gamma}_{R_j D} \mathbf{C}_j \mathbf{d}_{R_j} + \mathbf{n}'_D \quad (25)$$

where \mathbf{n}'_D is the processed noise after the combiner $\mathbf{n}'_D = \mathbf{L}_j \mathbf{n}_D$. As a result of the described processing, the links between the $|\Omega|$ active relays and the destinations are now spatially separated and single user like techniques can be used to reach the capacity of each equivalent channel $\tilde{\mathbf{U}}_{R_j D}^{(0)H} \mathbf{\Gamma}_{R_j D}$, $j \in \Omega$. In particular, as for the downlink case described in the previous section, the matrices \mathbf{D}_j and \mathbf{C}_j can be determined by performing the SVD of $\tilde{\mathbf{U}}_{R_j D}^{(0)H} \mathbf{\Gamma}_{R_j D}$ and using the waterfilling power allocation satisfying either the common power constraint (14) or the separated power constraint (15). We observe that \mathbf{L}_j and \mathbf{F}_j are unitary, and therefore the former does not affect the per-component variance of the additive noise at each antenna, whereas the latter does not affect the transmit power at the transmit side.

V JOINT DOWNLINK/UPLINK OPTIMIZATION

Let $\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2 \cup \dots \cup \mathcal{E}_{r+2}$ a set of selected eigenmodes for the downlink phase, and $\mathcal{I} = \mathcal{I}_1 \cup \mathcal{I}_2 \cup \dots \cup \mathcal{I}_{r+2}$ a set of selected eigenmodes for the uplink phase. Let $R_{SR_j}(\mathcal{E})$ the maximum mutual information between the source and the j th relay during the downlink phase under the assumption that the set of eigenmodes \mathcal{E} has been selected by means of the scheme described in Section III. Moreover, let $R_{R_jD}(\mathcal{I})$ the maximum mutual information between the j th relay and the destination during the uplink phase under the assumption that the set \mathcal{I} has been selected by means of the scheme described in Section IV. We recall that under the convention made in Section II the $(r+2)$ th relay corresponds to the source, and $R_{SR_{r+2}}(\mathcal{E}) = \infty$ for every \mathcal{E} , whereas the $(r+1)$ th relay corresponds to the destination, and $R_{R_{r+1}D}(\mathcal{I}) = \infty$ for every \mathcal{I} . The maximum mutual information between source and destination for a given couple $(\mathcal{E}, \mathcal{I})$ is given by

$$R_{SD}(\mathcal{E}, \mathcal{I}) = \frac{1}{2} \sum_{i=1}^{r+2} \min(R_{SR_i}(\mathcal{E}), R_{R_iD}(\mathcal{I})) \quad (26)$$

The maximum mutual information between source and destination with respect to all the possible couples $(\mathcal{E}, \mathcal{I})$ is given by

$$R_{SD}^* = \max_{(\mathcal{E}, \mathcal{I})} R_{SD}(\mathcal{E}, \mathcal{I}). \quad (27)$$

Problem (27) involves a brute force search over all the possible relay/eigenmode allocations. In order to lower the computational complexity, we propose an iterative downlink/uplink greedy optimization algorithm where the set of active eigenmodes \mathcal{E} and \mathcal{I} are updated in an iterative way. The proposed algorithm is composed by two loops: the external loop updates the value of \mathcal{E} , whereas the internal loop, for each candidate \mathcal{E} , calculates the "best" (in a greedy sense) set \mathcal{I} . We define as $\mathcal{E}^{(m)*}$ the value of \mathcal{E} found at the m th stage of the external loop. We emphasize that this value does not correspond to the optimum one that would have been obtained by a brute force search over $\sum_{l=1}^{\min(m, N_s)} \left(\frac{(\sum_{j=1}^{r+2} N_j)!}{(\sum_{j=1}^{r+2} N_j - l)! l!} \right)$ candidates, where $N_j = N_r$ if $1 \leq j \leq r$, $N_j = N_d$ if $j = r+1$ and $N_j = N_s$ if $j = r+2$. The candidate set $\mathcal{E}^{(m)}$ is defined as

$$\mathcal{E}^{(m)}(j, l) = \mathcal{E}^{(m-1)*} \bigcup_{\Sigma_{SR_j, l} \notin \mathcal{E}^{(m-1)*}} \Sigma_{SR_j, l}. \quad (28)$$

where $j = 1, \dots, r+2$ and $l = 1, \dots, \min(N_s, N_j)$. Let's define $\mathcal{E}^{(0)*} = \phi$, where ϕ is the empty set. The value found at the end of the m th iteration of the external loop is given by

$$\mathcal{E}^{(m)*} = \arg \max_{\mathcal{E}^{(m)}(j, l)} R_{SD}(\mathcal{E}^{(m)}(j, l), \mathcal{I}^*(\mathcal{E}^{(m)}(j, l))) \quad (29)$$

where $\mathcal{I}^*(\mathcal{E}^{(m)}(j, l))$ is the best (in a greedy sense) eigenmode allocation for the uplink part given the downlink eigenmode allocation $\mathcal{E}^{(m)}(j, l)$. With the same motivations of the outer loop, also in the inner loop we use a greedy selection algorithm to find $\mathcal{I}^*(\mathcal{E}^{(m)}(j, l))$. Leaving implicit the dependence on

$\mathcal{E}^{(m)}(j, l)$, we define a possible candidate set $\mathcal{I}^{(n)}$ during the n th iteration of the inner loop as

$$\mathcal{I}^{(n)}(u, v) = \mathcal{I}^{(n-1)*} \bigcup_{\Sigma_{R_u D, v} \notin \mathcal{I}^{(n-1)*}} \Sigma_{R_u D, v}. \quad (30)$$

Let $\mathcal{I}^{(0)*} = \phi$. The uplink eigenmode allocation set found at the end of n th iteration of the external loop is given by

$$\mathcal{I}^{(n)*}(\mathcal{E}^{(m)}(j, l)) = \arg \max_{\mathcal{I}^{(n)}(u, v)} R_{SD}(\mathcal{E}^{(m)}(j, l), \mathcal{I}^{(n)}(u, v)). \quad (31)$$

Leaving implicit the dependence of $\mathcal{I}^{(n)*}$ and $\mathcal{I}^{(n-1)*}$ on $\mathcal{E}^{(m)}(j, l)$, if the following condition is found at the n th iteration of the inner loop

$$R_{SD}(\mathcal{E}^{(m)}(j, l), \mathcal{I}^{(n)*}) < R_{SD}(\mathcal{E}^{(m)}(j, l), \mathcal{I}^{(n-1)*}), \quad (32)$$

the inner loop is stopped and the value $\mathcal{I}^*(\mathcal{E}^{(m)}(j, l)) = \mathcal{I}^{(n-1)*}$ is returned to the outer loop. In the same way, at the m th iteration of the outer loop if the following condition is found

$$R_{SD}(\mathcal{E}^{(m)*}, \mathcal{I}^*(\mathcal{E}^{(m)*})) < R_{SD}(\mathcal{E}^{(m-1)*}, \mathcal{I}^*(\mathcal{E}^{(m-1)*})), \quad (33)$$

the loop is interrupted and the couple $(\mathcal{E}^{(m-1)*}, \mathcal{I}^*(\mathcal{E}^{(m-1)*}))$ is returned as output of the algorithm.

VI SIMULATION RESULTS

In order to simulate the performance of the proposed scheme we consider a scenario with $r = 9$ relays. Let d the distance between source and destination and let $(0, 0)$ and $(0, d)$ be the spatial coordinates of respectively source and destination. The spatial coordinates of the nine relays are given by $(\frac{d}{4}, -\frac{d}{4})$, $(\frac{d}{4}, 0)$, $(\frac{d}{4}, \frac{d}{4})$, $(\frac{d}{2}, -\frac{d}{4})$, $(\frac{d}{2}, 0)$, $(\frac{d}{2}, \frac{d}{4})$, $(\frac{3d}{4}, -\frac{d}{4})$, $(\frac{3d}{4}, 0)$, $(\frac{3d}{4}, \frac{d}{4})$. The distance between source and destination is a parameter fixed such that the SNR at the destination has a given value. Each node is equipped with $N_s = N_d = N_r = 4$ antennas. For simulating the signal propagation between the different nodes we used the WINNER channel generator [8], and in particular the propagation scenario B1 (typical urban microcell), modified such that all the nodes have the same height of 3 meters. We considered both line-of-sight (LOS) and not line-of-sight (NLOS) propagation, with 0.5λ and 10λ antenna element distance. The performance is given in terms of throughput [bit/s/Hz] vs source destination SNR. We compare four different techniques:

- the proposed data splitting algorithm (DSA) under the per-relay power constraint (15);
- the proposed DSA algorithm performance under the common power constraint (14);
- the 'best relay selection' scheme, obtained by selecting the best relay and transmitting at the closed loop capacity [9] in each of the two links (source to relay and relay to destination);

- the direct link transmission scheme, obtained by using the closed loop capacity formula of the link between source and destination.

In Figure 2(a) a propagation scenario without line of sight is considered, for 10λ antenna element spacing (dash/dotted line) and 0.5λ antenna element spacing (continuous line). We note that with correlated channels (0.5λ case) the DSA gives a not negligible gain with respect to best relay selection scheme and direct link transmission scheme, in the entire SNR region.

Let's for the moment consider the case of common power constraint (14). In this case the gain is due to two factors. The first factor is that by splitting the streams between different relays, the effective degrees of freedom (EDOF) [10] is not limited by the rank of a single link channel (*effective degrees of freedom gain*). The second factor is that the proposed greedy relay/eigenmode allocation scheme at each channel generation selects the best set of spatial channels (*multirelay diversity gain*). When we consider a per-relay power constraint (15), to the already described two factors that occur also in the case of common power constraint (14), we add also the effect of the power gain in the uplink phase. When the channel is not correlated this power gain still involves a performance improvement at low SNR, whereas by directly transmitting all the streams to the destination (direct link transmission) we are already able to exploit all the effective degrees of freedom.

In Figure 2(b) the same scenario is considered for a LOS case. We note that with correlated channels (0.5λ case) the DSA gives a not negligible gain with respect to best relay selection scheme and direct link transmission scheme, in all the SNR region. In this case the effect of effective degrees of freedom gain and multirelay diversity gain are even more pronounced and involve a big advantage of the DSA over the two baselines, for both 0.5λ antenna element spacing and 10λ antenna element spacing.

VII CONCLUSIONS

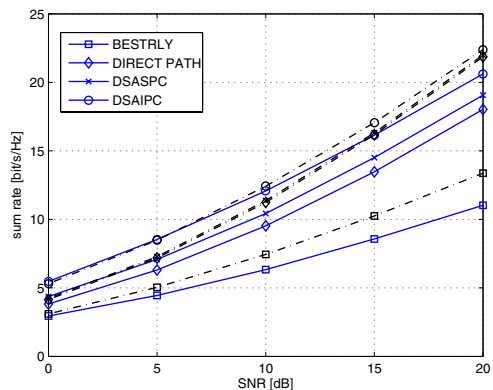
In this paper, we have presented an algorithm for high data rate transmission in a wireless relay network. Our proposed algorithm splits the data at the source into multiple independent data streams. These data streams are then forwarded to the destination via some selected relays at the same time. The relays are selected using an opportunistic approach based on spatially decomposing the channels and accessing the best modes. Simulation results have shown the benefits of our algorithms.

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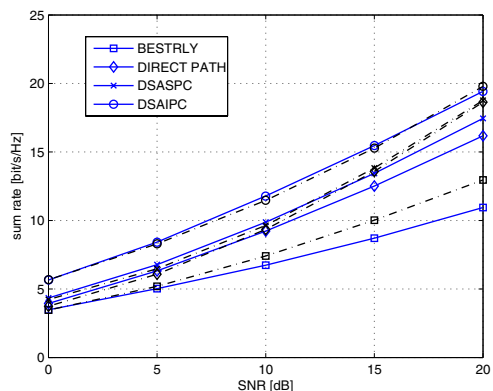
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(a)



(b)

Figure 2: Performance comparison between the different considered schemes. In each node 4 antennas has been considered with an element spacing of 10λ (dash/dotted line) and 0.5λ (continuous line). A WINNER B1 propagation scenario has been used [8]. 2(a): without LOS. 2(b): with LOS.

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