Relay Transmission Schemes with Multiple Antennas for Wireless Backhaul Networks

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Abstract— **Herein, we propose a novel data splitting algorithm for high throughput relay transmissions using multiple antennas. We also study a two-path relaying protocol using multiple antennas for rural/macro-cell scenarios where a cellular setup is deployed. The performance improvements are demonstrated via simulations.**

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.

Different relay protocols have been studied widely to improve the spectral 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 implement. This, however, generates a pre-log factor $\frac{1}{2}$ for the overall system throughput and may therefore limit the achievable spectral efficiency. More spectral efficient protocols have been 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 spatio-temporal transmission schemes have been extended to the multiple-input multiple-output (MIMO) cooperative systems. In [5], protocols have been designed to use the space-time codes in cooperative wireless networks. Spatial multiplexing techniques have also been proposed to be used in distributed MIMO systems [6].

In this paper we present two different approaches for wireless backhaul networks, namely the data splitting algorithm and two-path relaying. The first approach is more interesting for urban transmission where large number of relays are available. The second approach is more suitable for the rural/urban macro-cell scenario with cellular setups. This paper is organized as follows. We propose the data splitting algorithm in Section II. In Section III, the two-path relaying protocol is studied for the nodes equipped with multiple antennas. Simulation results are presented in Section IV. Finally, we conclude in Section V.

II. DATA SPLITTING ALGORITHM

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.

A. Concept

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. The transmission protocol is summarized in Table I.

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

TABLE I
TRANSMISSION PROTOCOL.

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 $\mathbf{H}_{SR_i}, \quad i = 1, \dots, r$ the $N_R \times N_S$ channel matrix between the source and the ith relay and by $\mathbf{H}_{R_iD}, \quad i = 1, \dots, r$ by $N_D \times N_R$ the channel matrix between the ith relay and the destination.

The transmission protocol described in Table I 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 a follows

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

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

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

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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.

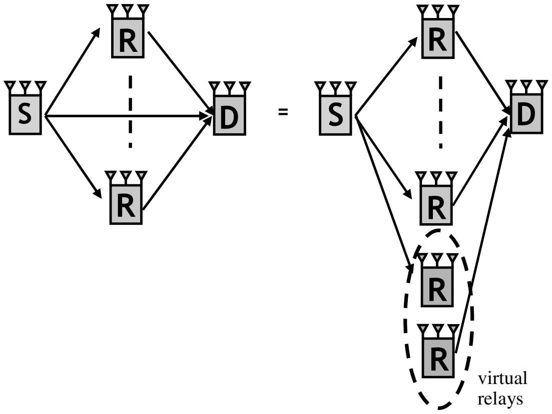

Fig. 1. Equivalence between original system with direct link between source and relays and equivalent system, where the direct link is modeled by means of two virtual relays.

B. Downlink phase

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

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

$\mathbf{x}_S$ 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

$$\mathbb{E}\left[tr\left[\mathbf{x}_s\mathbf{x}_s^H\right]\right] \leq P. \tag{4}$$

and can be written as

$$\mathbf{x}_s = \sum_{j\in\Phi}\mathbf{G}_j\mathbf{d}_{SR_j} \tag{5}$$

where $\mathbf{G}_j$ is the $N_S \times |\mathcal{E}_j|$ complex precoding matrix associated to the jth active relay, $\mathbf{d}_{SR_j}$ is the $|\mathcal{E}_j| \times 1$ data symbol vector sent to the jth active relay, and $\mathcal{E}_j$ is the set of eigenmodes (or spatial dimensions) allocated to the jth active relay.

The downlink channels $\mathbf{H}_{SR_j},$, $\quad j \in \Phi$ can be spatially decomposed using the algorithm proposed in [7] for a downlink transmission. The considered technique uses a joint eigenmode/relay selection scheme where the set of active eigenmodes is selected in a greedy manner to maximize the sum-rate of the system. We refer to [8] for more details about the proposed technique.

C. Uplink phase

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

$$\mathbf{y}_D = \sum_{j\in\Omega}\mathbf{H}_{R_jD}\mathbf{x}_{R_j} + \mathbf{n}_D \tag{6}$$

where $\mathbf{x}_{R_j}$ is the $N_R \times 1$ vector transmitted by the ith 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 the following power constraints at each relay

$$E\left[\left[||\mathbf{x}_{R_j}||_2^2\right]\right] \leq P, \quad j \in \Omega. \tag{7}$$

The signal transmitted at the jth relay can be written as

$$\mathbf{x}_{R_j} = \mathbf{F}_j\mathbf{d}_{R_j} \tag{8}$$

where $\mathbf{F}_j$ is the $N_R \times |\mathcal{I}_j|$ precoding matrix used at the jth active relay, whereas $\mathbf{d}_{R_j}$ is the $|\mathcal{I}_j| \times 1$ data symbol vector transmitted from the jth relay and $|\mathcal{I}_j|$ is the set of eigenmodes allocated to the jth active node during the uplink phase. The uplink channel 6 can be spatially decomposed by using an extension of the algorithm proposed in [7] for the uplink case. We refer to [8] for more details about the proposed technique.

D. Joint Downlink/Uplink Optimization

Let $\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2 \cup \ldots \cup \mathcal{E}_{r+2}$ a set of selected eigenmodes for the downlink phase, and $\mathcal{I} = \mathcal{I}_1 \cup \mathcal{I}_2 \cup \ldots \cup \mathcal{I}_{r+2}$ a set of selected eigenmodes for the uplink phase. Let $R_{SR_j}(\mathcal{E})$ the maximum mutual information between the source and the jth 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 II-B. Moreover, let $R_{R_jD}(\mathcal{I})$ the maximum mutual information between the jth 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 II-C. 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

$$R_{SD}\left(\mathcal{E}, \mathcal{I}\right) = \frac{1}{2}\sum_{i=1}^{r+2}\min\left(R_{SR_i}(\mathcal{E}), R_{R_iD}(\mathcal{I})\right) \tag{9}$$

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

$$R_{SD}^* = \max_{(\mathcal{E},\mathcal{I})} R_{SD}\left(\mathcal{E}, \mathcal{I}\right). \tag{10}$$

Problem (10) 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 $\mathcal{I}$.

III. TWO-PATH RELAYING USING MULTIPLE ANTENNAS

In this section, we focus on studying the rural/urban macro-cell scenario where the cellular setups are often used. We consider two hops transmission, and assume no direct link between non-neighboring cells. Hence the source node S needs to communicate with the destination node D via relay nodes R1 and R2 (see Figure 2). Note that all the other neighboring cells are too far away from D, and therefore they cannot be used as relays in this two-hop network.

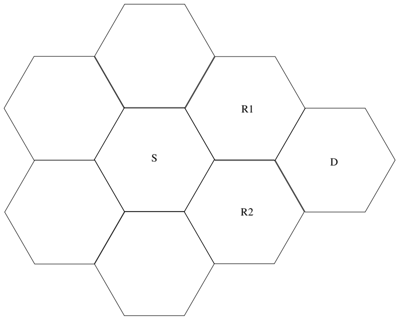

Fig. 2. Targeting scenario for the relaying transmissions using two relays.

A. Two-path relaying protocol

The two-path relaying protocol has recently been proposed in [3], [4] to improve the spectral efficiency of the relay network. It works as follows:

- In the first time slot, the source node S transmits data stream 1 to relay node R1.
- In the second time slot, S transmits data stream 2 to R2, and R1 forwards data stream 1 to D. Note that during this process, the transmission between R1 and D interferes the transmission between S and R2.
- In the third time slot, S transmits data stream 3 to R1, and R2 forwards data stream 2 to D. The transmission between R2 and D interferes the transmission between S and R1.

The second and third steps repeat continuously during the rest transmission time slots. This means the destination node D receives data streams from R1 in the even time slots, and from R2 in the odd time slots (except the first time slot). Assume there are M time slots used for transmission, the multiplexing ratio for this algorithm is [4]

$$\text{Ratio} = \frac{M-1}{M} \tag{11}$$

When M is large, the multiplexing ratio can be approximately seen as 1. Therefore, comparing to the other relay protocols [2] where a pre-log factor 1/2 exists for the overall system throughput, the spectral efficiency has been greatly improved.

The main problem for this two-path relaying protocol is the interference between two relays: when the source transmits to one relay, at the mean time the other relay forwards the data to the destination. When multiple antennas are deployed at the relay nodes, it is possible to cancel the inference by sacrificing some spatial degree of freedom, instead of simply treating the interference as noise.

B. System model

When multiple antennas are deployed at each node, the received signal at the relay i can be written as

$$\mathbf{r}_{s,r_i} = \mathbf{H}_{s,r_i}\mathbf{P}_{s,r_i}\mathbf{s}_{r_i} + \mathbf{H}_{r_k,r_i}\mathbf{P}_{r_k,d}\mathbf{s}_{r_k} + \mathbf{n}_{s,r_i} \tag{12}$$

where s, r_i, r_k and d denote source node, relay nodes and destination node respectively. $\mathbf{H}_{m,n}$ is the channel matrix between node m and node n, $\mathbf{P}_{m,n}$ is the precoding matrix for the transmission between node m and node n.

At the mean time, the received signal at the destination node can be expressed as

$$\mathbf{r}_{r_k,d} = \mathbf{H}_{r_k,d}\mathbf{P}_{r_k,d}\mathbf{s}_{r_k} + \mathbf{n}_{r_k,d}. \tag{13}$$

In this paper, we consider two possible multiple antenna transmission schemes that can be used to relay the information to the destination node as described below.

C. Treat the interference as noise

The first approach is simply treating the interference as noise, similar to the approach used in [3], [4]. In this case, the precoding matrix $\mathbf{P}_{s,r_i}$ and $\mathbf{P}_{r_k,d}$ are simply determined by the waterfilling algorithm [9].

When the source to relay link is stronger than interference link, the capacity for $\mathbf{H}_{s,r_i}$ can be obtained from [10], i.e.

$$C_{s,ri} = \log_2 \det(\mathbf{I} + \mathbf{H}_{s,r_i}\mathbf{P}_{s,r_i}\mathbf{P}^H_{s,r_i}\mathbf{H}^H_{s,r_i}\mathbf{R}^{-1}_{r_k,r_i}) \tag{14}$$

where $\mathbf{R}_{r_k,r_i} = \mathbf{H}_{r_k,r_i}\mathbf{P}_{r_k,d}\mathbf{P}^H_{r_k,d}\mathbf{H}^H_{r_k,r_i} + \mathbf{I}$.

When the source to relay link is weak comparing to the interference link, we can first decode and cancel the interference signal, and then decode $\mathbf{s}_{r_i}$ interference free [3], [4].

The capacity for $\mathbf{H}_{r_k,d}$ can be easily obtained using waterfilling algorithm [9], i.e.

$$C_{rk,d} = \log_2 \det(\mathbf{I} + \mathbf{H}_{r_k,d}\mathbf{P}_{r_k,d}\mathbf{P}^H_{r_k,d}\mathbf{H}^H_{r_k,d}) \tag{15}$$

Note that if the interference signal is decoded first at the relay node, the capacity for the link between relay to the destination becomes the minimum of $C_{r_k,d}$ and the capacity of the interference link C_{r_k,r_i}.

For each relay node, the capacity from source to destination can be obtained by taking the minimum between the capacity of source to relay and the capacity of relay to destination. Finally, the overall system throughput C^N_{sys} is the mean of the capacity of both relays.

D. Interference cancellation

Let us consider the link between relay k to the destination node. The precoding matrix $\mathbf{P}_{r_k,d}$ is determined first by using the waterfilling algorithm to allocate power to spatial subchannels associated with the L largest singular values of $\mathbf{H}_{r_k,d}$, where L is the number of streams transmitted from relay k to destination simultaneously. Note that the total number of data streams transmitted from source to relay i

and from relay k to destination at the same time slot cannot exceed the number of antennas deployed at relay i.

Since the propagation scenarios considered in the wireless backhaul network are quite stationary, it is reasonable to assume that relay i knows the precoding matrix $\mathbf{P}_{r_k,d}$ used at relay k via feedback channel. We then use the zero-forcing (ZF) technique to cancel the interference from relay k. This can be done by applying the singular value decomposition on $\mathbf{H}_{r_k,r_i}\mathbf{P}_{r_k,d}$, i.e.

$$\mathbf{H}_{r_k,r_i}\mathbf{P}_{r_k,d} = [\mathbf{U}^{(1)}_{r_k,r_i}, \mathbf{U}^{(0)}_{r_k,r_i}]\mathbf{\Sigma}_{r_k,r_i}\mathbf{V}^H_{r_k,r_i} \qquad (16)$$

where $\mathbf{U}^{(0)}_{r_k,r_i}$ corresponds to the right singular vectors that lie on the null space of $\mathbf{H}_{r_k,r_i}\mathbf{P}_{r_k,d}$. By multiplying the ZF matrix $(\mathbf{U}^{(0)}_{r_k,r_i})^H$ to the received signal $\mathbf{r}_{s,r_i}$, the interference can be completely removed.

Assume the source node S knows the ZF matrix used at relay i via feedback channel, the precoding matrix $\mathbf{P}_{s,r_i}$ can then be determined by applying the waterfilling algorithm on $(\mathbf{U}^{(0)}_{r_k,r_i})^H\mathbf{H}_{s,r_i}$.

Since the interference is completely removed by ZF approach, we can now easily obtain the capacity for the link between source node to relay nodes, and relay nodes to destination node. For each relay, the capacity between source to destination can be calculated as the minimum of the capacity between source to the relay and the capacity between the relay to destination. The overall system throughput C^{ZF}_{sys} is the mean of the capacity of both relays.

E. *Optimal switching*

For each independent channel realization, one of the above transmission scheme may offer larger throughput than the other. By selecting the optimal scheme between the above two schemes, we can obtain higher system throughput as

$$C_{opt} = \max(C^{N}_{sys}, C^{ZF}_{sys}). \qquad (17)$$

IV. SIMULATION RESULTS

A. *Data Splitting Algorithm*

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 [11], 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 (7);
- 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 3 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. The gain is due to three factors. The first factor is that by splitting the streams between different relays, the effective degrees of freedom (EDOF) [12] 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*). The third factor is 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.

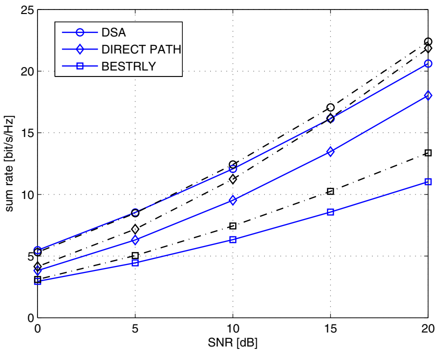

Fig. 3. Performance comparison between the different considered schemes. In each node 4 antennas has been considered with an element spacing of 10λ (dash/dotted line) and 0.5λ (continuous line). A WINNER B1 NLOS propagation scenario has been used [11]

B. *Two-path relaying*

In this part, we present simulation results for the two-path relaying protocol with each node equipped with 4 antennas. The modified WINNER C2 channel model [11] is used to simulate the urban macro-cell NLOS scenario. 100 channel realizations are generated with 2λ inter-element distance between neighboring antennas. For the two path relaying with interference cancelation, we assume at each time slot, source transmits two streams to relay i and relay k forwards two

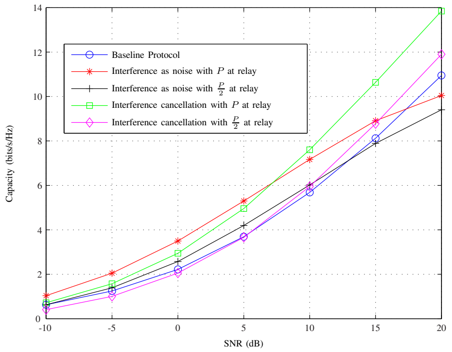

Fig. 4. Simulations of two-path relaying protocols using multiple antennas with 2λ inter-element distance in urban macro-cell NLOS scenario.

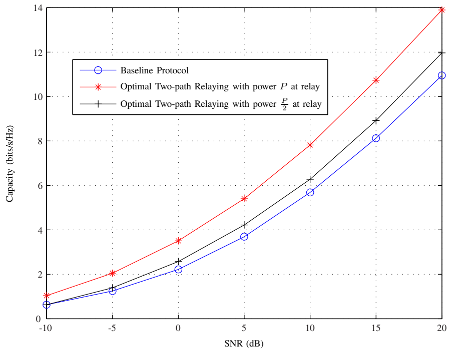

Fig. 5. Optimal switching for two-path relaying protocol using multiple antennas

streams to destination, so that relay i has two degree of freedom to cancel the interference from relay k.

Two power allocation schemes are used at relay nodes. The first one is to transmit using power P at each relay. The other scheme is to transmit using power $\frac{P}{2}$ at each relay so the the sum power for two relays is P. The protocol used as a baseline for the purpose of comparison is to transmit through one relay that can provide higher throughput than the other [2].

Fig. 4 shows the mean throughput results for the urban macro-cell NLOS scenario. It is clearly shown that two-path relaying protocol transmitting with full power P at each relay performs better than the baseline protocol for both transmission schemes with and without interference cancelation. When the total power in the network is constrained (i.e. each relay transmits with power P/2), the two-path relaying protocol without interference cancelation still provides higher throughput than the baseline protocol. The two-path relaying protocol with interference cancelation, however, performs worse than the baseline protocol in the low SNR region and better in the high SNR region.

Comparing the two-path relaying protocol with and without interference cancelation, it is clearly shown in Fig. 4 that in the low SNR region, the mean throughput for the two-path relaying without interference cancelation is higher than throughput provided by the scheme with interference cancelation. When the SNR increases, the throughput of the two-path relaying with interference cancelation increases since this scheme completely cancels the interference and the throughput only depends on the SNR at the receive side. The throughput of the two-path relaying without interference cancelation, however, is limited by the interference between two relays in the high SNR region.

Using the optimal switching between the two-path relaying with/without interference cancelation, Fig. 5 shows that the performance of the two-path relaying further improved and throughput is higher than using the baseline protocol over all simulated SNR region.

V. CONCLUSIONS

In this paper, we have studied two approaches for high data rate relay transmission with multiple antennas. A data splitting algorithm has been proposed for urban scenarios where multiple relays are available. For rural/macro-cell scenarios where a cellular setup is often deployed, the two-path relaying protocol using multiple antennas has been studied. Simulation results have shown that both approaches provide significant gains comparing to the conventional relay transmission scheme.

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