

Combining MIMO and Relaying Gains for Highly Efficient Wireless Backhaul

(Invited Paper)

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Abstract— In this paper, the design of a highly efficient and flexibly deployable wireless backhaul is addressed as a promising alternative to the typical wired solutions. To this end, a novel approach for relay transmissions with multiple antennas is proposed in the framework of wireless meshed backhaul system design optimization. The link and system level performance are assessed and different mesh topologies and relaying protocols are investigated. The optimality of the approach relies on the reconfigurable /adaptive use of the degrees of freedom offered by the combination of multiple antennas and relays and is promising for both wireless backhaul and access applications.

I. INTRODUCTION

THE ongoing proliferation of wireless broadband data services is expected to lead to increased needs on the side of the backhaul network, which transports data between the access network and the wired Internet. Furthermore, the envisioned reconfigurable design of future networks (e.g. LTE-ADVANCED, IEEE 802.16m) will rely on an adaptively optimized mix of distributed versus centralized network management techniques. The latter may include advanced air interface features, such as coordinated transmission between different access points, as a means of enhancing throughput performance especially at the cell edge. In such approaches, backhaul requirements are key in ensuring feasibility. Moreover, the paradigm shift from the traditional cellular deployment to more hierarchical/self-organized approaches characterized by the femto cell concept will further emphasize the need for highly performing and fast deployable backhaul solution.

The wired infrastructure currently in use to support the second and third generation cellular networks may – in the light of the above described trend – prove inadequate to support the projected broadband data load and the associated advanced air interface and networking features. The conventional upgrading to high-speed fiber connections is indeed taking place in many locations. However, this

upgrading is a costly and time-consuming undertaking and quite often not the preferred solution by the operators, who are looking for promising alternatives, especially to address the curb to the home or enterprise backhaul links.

On the other hand, wireless data services are a social good that is especially needed in remote and isolated areas that have a poor wired network infrastructure. While wireless data access technologies can make up to a large extent for the lack of wired access, these can be only offered if accompanied by an accordingly sized backhaul network. The required investment and time for bringing cable and/or fiber in these areas may often imply unrealistic business models and local operators and service providers are looking at cost efficient and fast deployment solutions.

An efficient wireless backhaul solution should be therefore characterized by a number of requirements related to: i) Quality of Service, in terms of end-to-end throughput and delay, coverage and overall capacity; ii) Flexibility / Adaptivity to various topologies and propagation conditions; iii) Heterogeneity / Openness with respect to applicability of the concepts and algorithms to various air interface and network designs.

II. COMBINING MIMO AND RELAYING GAINS: THE MEMBRANE APPROACH

In order to provide a highly performing and cost-efficient solution for wireless backhaul applications, a new approach is proposed [1] based on an adaptive, multihop (mesh) networking design that makes use of channel state information for advanced Multiple Input Multiple Output (MIMO) processing, spatial and relaying gains combination and cross-layer optimized resource allocation and routing.

The use of relays, especially for wireless backhauling purposes, where the objective is to replace wires with efficient/robust wireless links, is targeting –at a first degree – the range extension and coverage optimization. Since full-duplex relaying implementation is considered not feasible, half-duplex relaying immediately introduces a factor of $\frac{1}{2}$ in the achievable throughput, meaning that the use of relaying

alone can provide coverage enhancements at the expense of the overall capacity.

The introduction of multiple antenna processing at the relay nodes was investigated as a means to improve the spectral efficiency of relay networks by exploiting spatial multiplexing, diversity and interference mitigation gains [2][3]. Furthermore, MIMO concepts have been extended to a cooperation framework [4], where protocols are designed applying space-time processing across different relay nodes, in a form of a distributed MIMO approach.

The notion of “multi-hop diversity” to enhance link reliability in diversity-limited fading environments is discussed in [5]. Cross-layer aspects are further explored in [6] on how to exploit multiuser diversity in a relay-assisted cellular scenario. These studies exemplify the fact that *performance optimization, in terms of both coverage and throughput-delay, of a multihop network is a cross-layer problem of jointly designing the transceiver, relay protocol and resource allocation / routing schemes.*

In this paper, we investigate –in a wireless backhaul system context- the system level performance in a 2-hop mesh network of a novel approach for high data throughput relay transmissions with multiple relays equipped with multiple antennas [7].

The basic idea is to split the main data stream into multiple independent spatial sub-streams and send it to a number of relays, during the first hop, and then to successfully collect them at the destination, during the second hop. The relays selection -out of all available relays- is based on 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.

As explained in [7] and illustrated in Figure 1, the Data Splitting Algorithm (DSA) divides the relay transmission in two ‘phases’ corresponding to each one of the to hops and optimizes transmission during the first hop (‘virtual downlink’) based on the principle of Multi-user Eigenmode Transmission (MET) originally proposed for downlink multiuser MIMO transmissions and extended here to the multiple relay case. During the second hop (‘virtual uplink’), the processing of signals from different relays at the destination is based on the uplink equivalent of the MET scheme.

The link level performance of DSA is investigated in [7] under two different power constraints: a sum power constraint (SPC) over all relays and independent power constraints (IPC) on each relay. One could further argue that a SPC is a reasonable assumption when power consumption and energy efficiency are of importance in a certain deployment, as it may be in the case of user-owned access point serving as candidate relay nodes (like in a femto cell scenario). On the other hand, this may not be the case in a wireless backhaul network consisting of fixed node topology (deployed by the operator), and there IPC may be a reasonable assumption.

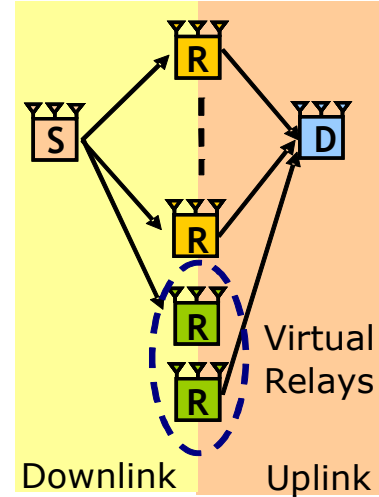


Figure 1 The Data Splitting Algorithm concept

The direct path and best relay transmission schemes are also evaluated for comparison. As expected and shown in [7], substantial link level throughput gains are obtained especially in the case of IPC.

The natural question that arises when considering a scheme such as DSA for wireless backhaul throughput enhancements, is whether and under which conditions the link level gains are preserved in a realistic deployment scenario. In this paper, we investigate the system level performance of the DSA-SPC in two different wireless backhaul deployment scenarios: i) a random relay node topology, where relay nodes are uniformly distributed within the cell area and candidate nodes are selected based on their vicinity to source and destination and ii) a fixed node topology, where nodes are equi-distantly placed on a circle centered at the access point. The objective of this study is to assess DSA system level performance and obtain some insight on the impact of the topology, in terms of relay nodes location and number.

III. SYSTEM ASSUMPTIONS AND PERFORMANCE EVALUATION

A. Simulation scenarios

We study a system with 7 cells, as depicted in Figure 2. Each cell has an access point located in the center of the cell. A number of nodes are uniformly distributed over the cell. We consider a first ring of interference with wraparound, i.e. the interference comes from the adjacent cells. The distance from the cell center to the cell edge is 500m, and its associated SNR is defined as the reference SNR. All the access points and nodes are deployed with 4-element antenna arrays. In this paper, we investigate the performance of backhaul networks using the DSA with sum power constraint (SPC) [7].

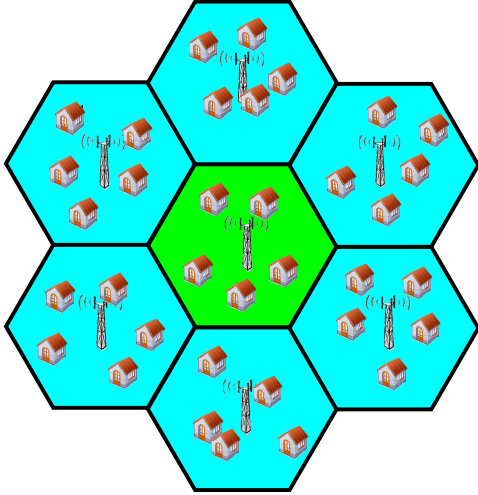


Figure 2 Simulation scenario: a 7-cell system

B. Propagation Channels

We consider both large scale and small scale channel variations. For the long-term channel variations, we use the well known pathloss model [8] with pathloss exponent $n=4$, i.e.

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right).$$

The shadowing effect is modeled by a log-normal shadowing model with 6dB standard deviation.

For the small-scale multi-path fading, we use the realistic WINNER II channel model [9]. In our simulations, we use the WINNER II D1 LOS channel model which simulates a rural Line-of-Sight (LOS) scenario. The inter-element distance is set to two wavelengths at the access points and half wavelength at all nodes.

C. Relay positions

The DSA requires a number of relays to assist the backhaul transmission from the access points to the end nodes. The relays can be specifically set up by the operators in the network design stage or one can use other existing nodes (except the current end nodes) as possible relay candidates. In our simulations, we study both cases respectively.

In the first case, we assume no specific relay nodes are set up by the operators. Therefore, the current end node will use other existing nodes in the cell as possible relays [10]. In order to limit the number of relay candidates to be considered in the cell, we select the nodes that are located in the area between the access point and the end node. To do that we plot two circles around the end node and the access point using the distance between the access point and the end node as the radius. The nodes that are located within the intersection region are used as relays for the DSA, as shown in Figure 3.

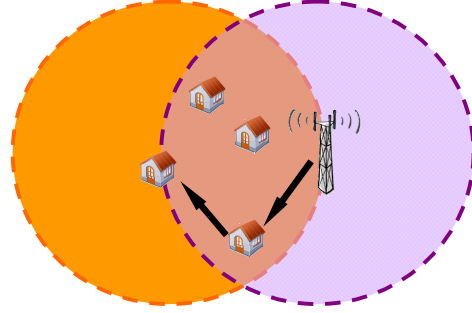


Figure 3 Relay node candidates within the cell

In the second case, we assume that a number of relay nodes are specifically set up by the operator [11]. These relays are equally positioned on a circle centered at the access point (cell center). The radius for the circle is half of the distance between the cell center to the cell boundary.

D. Simulation approach

In our simulation studies, a round robin scheduler is used independently at each cell. We use the *per node and per cell throughputs* as system level performance metrics. A two stage simulation is implemented to obtain the throughputs of the system.

In the first stage, all the precoding and receive matrices are identified at the access points, the relay nodes and the end nodes, using the DSA, assuming that the interference comes from the center of the other cells (This is an approximation since the interference from the relays in the other cells does not –in general- come from the center of the other cells).

We then use the obtained precoding and receive matrices in the second stage to calculate the real interference and Signal-to-Interference-Ratio (SINR). Based on the SINR, we calculate system throughput using the well-known capacity formula.

IV. SYSTEM LEVEL SIMULATION RESULTS

In this section, we study the performance of DSA with sum power constraint (DSA-SPC) using the developed system level simulator described above. We use the performance of the Direct Link transmission between the access points and end nodes as the benchmark. The Direct Link transmission scheme performance is obtained by using the closed loop capacity formula taking into account the real interference and SINR.

The performance of Hard Switching between the Direct Link transmission and the transmission using the best relay is also evaluated. Note that the best relay selection scheme involves selecting the best relay and transmitting at the closed loop capacity in each of the two links, source to relay and relay to destination.

The reference SNR in the system is set to 10dB. For each number of nodes / relays, 30 random node topologies are generated along with their corresponding channel realizations.

A. Random relay positions

In this part, we study the performance of DSA assuming different number of nodes in the cells. The per node and per cell throughputs are plotted in Figure 4 and Figure 5 respectively and the Cumulative Distribution Function (CDF) of the per node throughput in Figure 6. Note that when the number of nodes in the cell increases, the number of possible relay candidates increases as well.

In Figure 4, it is shown that when the number of nodes in the cell increases, the average *per node* throughput decreases. This is expected, since increased number of nodes results in reduced available resources for each node in the cell. DSA-SPC provides over 30% node throughput improvements as compared to the Direct Link transmission (no relaying) baseline and 15% improvements over the Hard Switching between Direct Link and Best Relay.

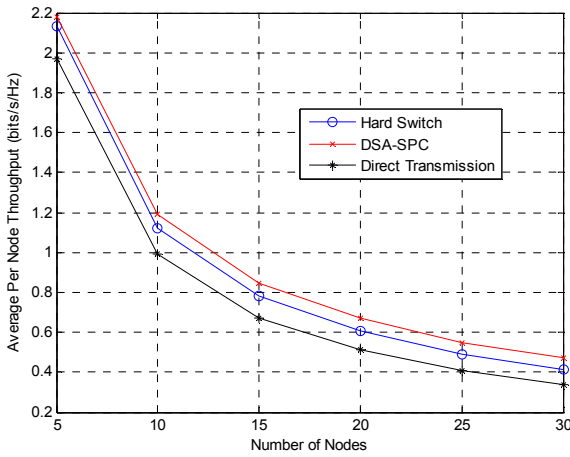


Figure 4 Per node throughput with random relay positions

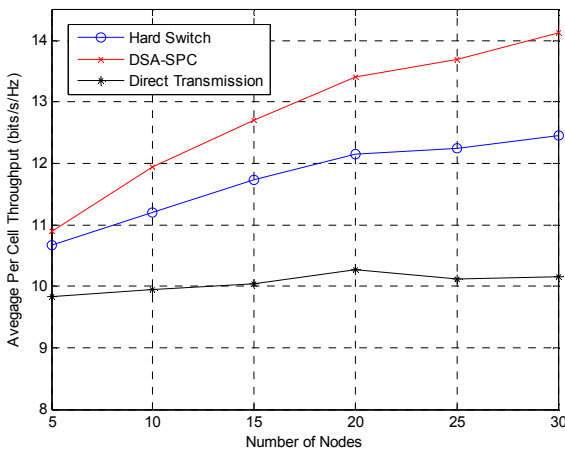


Figure 5 Per cell throughput with random relay positions

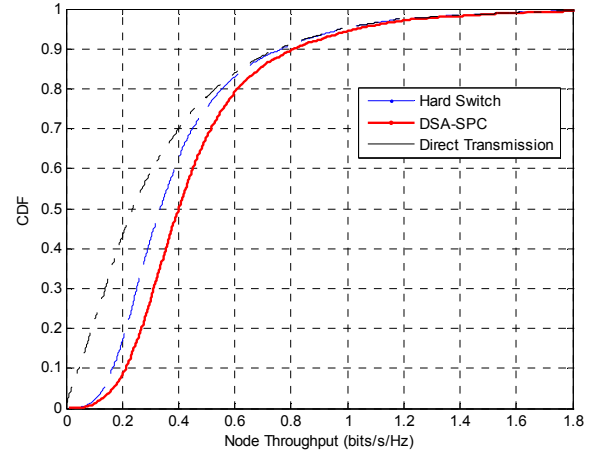


Figure 6 Cumulative Distribution Function of the per node throughput with random relay positions

Figure 5, on the other hand, clearly shows that although the per node throughput decreases, the overall per cell throughput increases when the number of nodes increases. In this case as well, DSA-SPC outperforms the Hard Switching algorithm and the Direct Link transmission by 15% and 35% respectively.

The CDF of the node throughput for the DSA is compared in Figure 6 with that of the Hard Switching and the Direct Link transmission schemes for the case of 30 nodes. It can be observed that relay transmission in general improves the outage performance (low throughput region) compared to the Direct Link transmission. For 10% probability the Hard Switching and DSA outperform Direct Link by a factor of 3 and 4 respectively.

B. Fixed relay positions

For fixed relay positions, we study the systems with 3/5/7/9 relay nodes assuming 10 (end) nodes uniformly distributed in each cell. The average per cell throughput is illustrated in Figure 7, which clearly shows that the cell throughput increases with the number of fixed relays.

We also plot in Figure 8 the DSA and Hard Switching throughput improvements (in percentage) over Direct Link transmission resulting from the increase in the number of fixed relays as a function of the number of fixed relays. It can be observed that increasing the number of relays from zero to 3, improves the DSA performance by around 18%. After that, further increase by two additional fixed relays provides less than 8% improvements in throughput.

Furthermore, both figures show the advantages of DSA compared to the Hard Switching algorithm and the Direct Link transmission.

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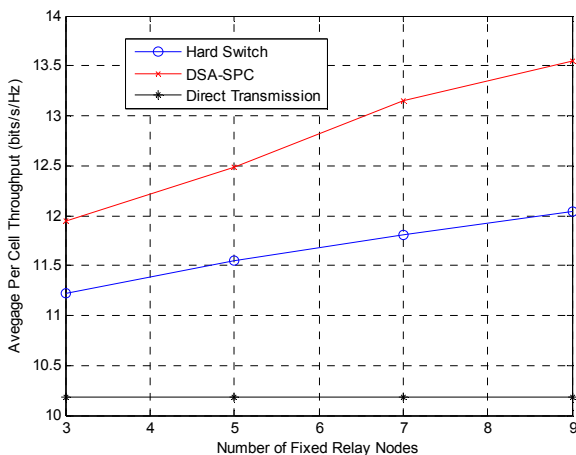


Figure 7 Per cell throughput with fixed relay positions

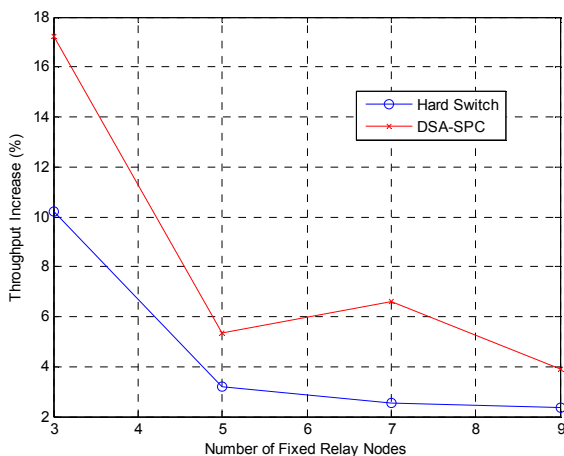


Figure 8 Throughput increase over the number of relays

V. CONCLUSIONS

In this paper, we have presented a novel approach for the efficient design of a multi-antenna multihop wireless backhaul network. Throughput enhancements are obtained by combining spatial and relay diversity gains in a jointly optimized transceiver-routing scheme based on the notion of data splitting. System level studies demonstrate the suitability of this approach in a realistic interference environment.

The investigation has not considered so far any particular resource allocation (only Round Robin scheme has been studied) or any interference management strategy. Extending the optimization framework to include these aspects is the objective of future work.

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