Opportunities, Constraints, and Benefits of Relaying in the Presence of Interference

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***Abstract*— In this paper the interference channel is extended by additional relay nodes in order to investigate the influence of interference on the design and performance of relaying protocols. We introduce a framework in which the relay interference channel is decomposed into a cascade of individual interference channels with finite conference links at the transmitters. Each of these stages is able to implement interference cancellation and mitigation schemes such as dirty-paper and Han-Kobayashi coding. We discuss the dependencies between individual stages and propose specific approaches with reasonable complexity. Finally, we compare the performance of these protocols using a simplified channel and geometry model of a mobile communications system. It shows that a reasonable choice is to coordinate the feeder links using distributed dirty-paper coding and to mitigate interference on the relay to user link using Han-Kobayashi coding.**

I. INTRODUCTION

A. Motivation

Multimedia applications draw more and more attention in mobile communications systems and they demand significantly higher data rates than voice service. An interesting option to satisfy these demands is to use relays, i. e., intermediate nodes support communication pairs by improving the channel conditions, improving frequency reuse through micro cells, and allowing for cooperative communication [1]. However, these nodes are an additional power source and hence inevitably increase the level of interference. An alternative are cooperative base station scenarios where multiple base stations are connected through conference links (backhaul) and mitigate interference by joint transmission and detection [2].

This paper concentrates on the analysis of the relay interference channel, i. e., we have a setup in which multiple communication pairs are supported by multiple relay nodes. Our focus is the integration of joint base station transmission and relaying as both strategies are likely candidates for next generation networks. Besides, we give first answers on the question how to combine the advantages of both strategies rather than using both separately as investigated in [3].

B. Interference channel

An interference channel [4] consists of two communication pairs which interfere with each other (see Fig. 1). It reflects the basic problem of mobile communications systems where two or more base stations serve user terminals. So far, the capacity of the Gaussian interference channel is not known for $a < 1$ and $b < 1$ in Fig. 1, i. e., the weak interference case. Han and Kobayashi introduced in [5] the best known coding strategy for this case: each transmitter divides its message in a common and private part where the former is decoded by both receivers while the latter one is only decoded by its dedicated receiver.

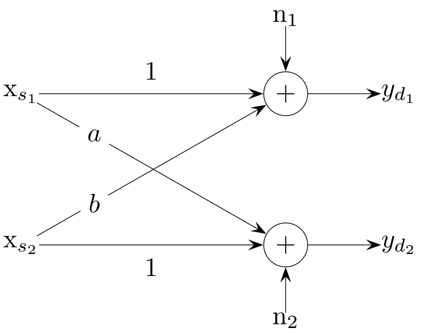

Fig. 1. Standard interference channel

Now, assume that both transmitters are connected by conference links (e. g. through a backhaul in mobile communications systems). In this scenario the Gaussian interference channel can be treated as a multiple antenna broadcast channel for which the capacity region was characterized in [6]. The capacity approaching strategy is Dirty-Paper Coding (DPC) [7] where each individual transmit-receive antenna pair is able to cancel part of the interference. Hence, DPC offers the possibility to coordinate different base stations as well as to implement cooperative transmissions of base stations and relay nodes.

C. Contribution of this work

The main contribution of this paper is to extend the interference channel by multiple relay nodes per communication pair. Although relaying is a promising concept it still needs to be clarified to which extent the increased interference level reduces the actual benefits of relaying. Based on the extended interference channel, we analyze different interference scenarios which occur in mobile communications systems. We simplify our model by not observing cooperation on user level (which

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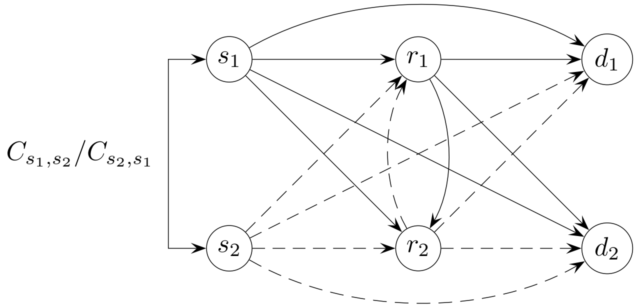


Fig. 2. Relay assisted interference channel with $S = 2, N = 1$ and $\mathcal{S} = \{s_1, s_2\}, \mathcal{R} = \{r_1, r_2\}, \mathcal{D} = \{d_1, d_2\}$.

could be feasible but would imply significant changes on the protocol stack), but we do consider practical aspects such as the fact that all relay nodes only operate in half-duplex mode. This paper proposes specific schemes that prove to be powerful and at the same time reasonably computational complex. We believe that these approaches can be promising candidates for next generation mobile communications networks.

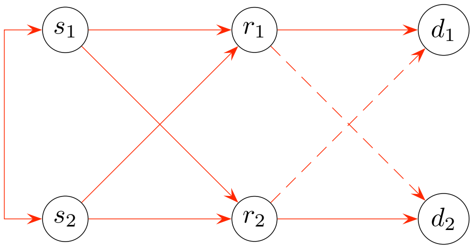
II. SYSTEM MODEL

In the following we will use italic letters (N or n) to denote constants, Ordered sets are denoted by $\mathcal{X}$, and $[b; b+k]$ is used to denote the ordered set of numbers $(b, b+1, \cdots, b+k)$ or $\emptyset$ if $k < 0$.

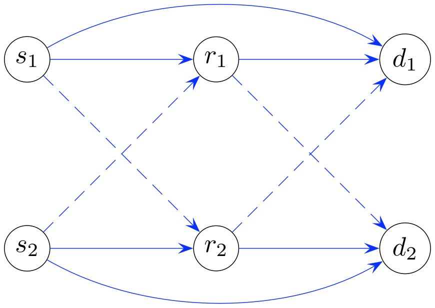
This paper considers a network with S different communication pairs modeling different base station to terminal connections in a mobile communications system. Each of these communication pairs (in the following also called paths) consists of a source node, N relay nodes and a destination node which is illustrated in Fig. 2 for $N = 1$ and $S = 2$. In the following, the sets of all source, relay and destination nodes are denoted by $\mathcal{S}$, $\mathcal{R}$, and $\mathcal{D}$, respectively. We assign to each node a state $\mathrm{M}_t \in \mathcal{M}_t = \{L, T\}$, defining whether the respective node is either *listening* or *transmitting*. Practical limitations imply an orthogonality constraint, i. e., a node is not able to be in both states at the same time. In contrast to source and relay nodes, all destination nodes are always listening, i. e. $\Pr\{\mathrm{M}_{\mathcal{D}} = \{L\}^S\} = 1$. The considered channel is time-invariant and defined over the channel inputs $\mathrm{x}_t \in \mathcal{X}_t$ and node states $\mathrm{m}_t \in \mathcal{M}_t$ with $t \in \{\mathcal{S}, \mathcal{R}\}$, the channel outputs $\mathrm{y}_t \in \mathcal{Y}_t$ with $t \in \{\mathcal{R}, \mathcal{D}\}$ and the pdf $p\left(\mathbf{y}_{\{\mathcal{R},\mathcal{D}\}} | \mathbf{x}_{\{\mathcal{S},\mathcal{R}\}}, \mathbf{m}_{\{\mathcal{S},\mathcal{R}\}}\right)$. We further consider conference links with finite capacities $C_{t,t'}$ $(t, t' \in \mathcal{S}$ and $t \neq t')$ between all source nodes used to coordinate their transmission.

III. PROTOCOLS AND CONSTRAINTS FOR $N = 1$ AND $S = 2$

To facilitate the presentation of the basic ideas we will concentrate in the following on the case of one relay per path ($N = 1$) and two communication pairs ($S = 2$) as illustrated in Fig. 2. In a mobile communications system this case models two radio access points which are supported by a relay node and communicating with a mobile terminal. Hence, it is of particular interest to analyze the influence and implications of interference in relay-assisted wireless communications system.



(a) Cascade of BC and IC. The first stage employs DPC using the conferencing links between both sources. The second stage might employ HK to mitigate the interference on the $\mathcal{R} \rightarrow \mathcal{D}$ links.



(b) Cascade of two ICs. The direct connection betwenn sources and destinations might be exploited by cooperative relaying.

Fig. 3. Two different ways to regard the cascade of both channels. Solid lines indicate useful transmission whereas dashed lines indicate interference which might be mitigated for instance using HK coding.

One way to examine this channel is to treat it as a cascade of two broadcast channels (BC) or interference channels (IC) which are interfering with each other. The first channel is from sources to relays ($\mathcal{S} \rightarrow \mathcal{R}$) and might exploit conference links between both sources. Depending on the respective coding schemes in this first channel, the second channel from relays to destinations ($\mathcal{R} \rightarrow \mathcal{D}$) must select the used encoding scheme. In case one of both channels is considered to be a BC, the transmitting nodes exploit common information (message *and* channel state information (CSI)) to coordinate their transmissions, e. g. using DPC. When treating one of both stages as IC the transmitting nodes do not exploit common information but might employ interference mitigation techniques such as Han-Kobayashi (HK) coding or transmitting on orthogonal resources. Table I illustrates the possible cascades.

Consider first the case when $\mathcal{R} \rightarrow \mathcal{D}$ is treated as IC. If the channel $\mathcal{S} \rightarrow \mathcal{R}$ is considered to be a BC, we can identify two basic strategies: DPC−Direct[1] where both source nodes employ DPC and joint precoding, both relay nodes coordinate their transmissions, and the destinations treat the other path's transmissions as noise. The second one is DPC−HK where both relay nodes employ HK coding to mitigate the

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[1] The abbreviation A−B is used to indicate that protocol A is used for $\mathcal{S} \rightarrow \mathcal{R}$ and B for $\mathcal{R} \rightarrow \mathcal{D}$.

		$\mathcal{S} \rightarrow \mathcal{R}$	
		BC	IC
$\mathcal{R} \rightarrow \mathcal{D}$	BC	DPC on both, $\mathcal{S} \rightarrow \mathcal{R}$ and $\mathcal{R} \rightarrow \mathcal{D}$	• HK or Direct on $\mathcal{S} \rightarrow \mathcal{R}$ • DPC on $\mathcal{R} \rightarrow \mathcal{D}$
	IC	• DPC on $\mathcal{S} \rightarrow \mathcal{R}$ • HK or Direct on $\mathcal{R} \rightarrow \mathcal{D}$	• HK or Direct on $\mathcal{S} \rightarrow \mathcal{R}$ • HK or Direct on $\mathcal{R} \rightarrow \mathcal{D}$

TABLE I

CLASSIFICATION OF POSSIBLE CASCADES

interference. Both protocols do not utilize any cooperative communication where the signals originating from the base station and relay node are combined. In the described cases this is not possible without a performance degradation as the BS can only optimize its DPC *either* towards the RNs *or* the destination but not both. Alternatively, both base stations and relay nodes could form one virtual antenna array employing DPC. In this paper, we do not consider this protocol as the necessity to exchange CSI and to synchronize the transmission would result in an immense signaling overhead and severe performance drop.

In case both source nodes are not connected or do not employ DPC, we have a cascade of ICs. For this case two interesting strategies result: HK−HK where both stages mitigate the interference using HK coding and Direct−Direct where both channels coordinate their transmission schedules and treat the other path's transmission as noise. The latter case, Direct−Direct, describes *relaying* with inter-path resource coordination. Here, we have two alternatives, non-cooperative relaying where the destination treats the source transmission as noise and hence only a *single* transmission path is used, and cooperative relaying where the destination exploits the source transmission and hence *multiple* transmission paths are exploited. Fig. 3 illustrates the resulting protocols.

In this paper, we do not consider the case where $\mathcal{R} \rightarrow \mathcal{D}$ is treated as a BC, i. e., both relays have common message information *and* exchanged CSI. In case we treat $\mathcal{S} \rightarrow \mathcal{R}$ as IC and employ HK, the commonly decoded information can be used for a distributed DPC and in case we treat $\mathcal{S} \rightarrow \mathcal{R}$ as BC, it degrades to a multicast channel. Nevertheless, the necessity to exchange CSI between both relays and to synchronize their transmissions might result in a severe performance degradation in a wireless communications system.

IV. APPLICATION TO A MOBILE COMMUNICATIONS SYSTEM

The focus of our work are mobile communications systems with frequency reuse 1, i. e., *all* resources are utilized in the whole cell area. This can be further enhanced by introducing relay-micro-cells such that each resource is used by multiple relay nodes within each cell. We apply the previously derived methods to investigate the interaction of relaying and distributed DPC (DPC by multiple, physically separated transmitters). Distributed DPC *exploits* interference instead of avoiding it or treating it as noise. Nevertheless, it requires precise channel state information at *all* transmitters which implies strong constraints on the coherence time and the required backhaul.

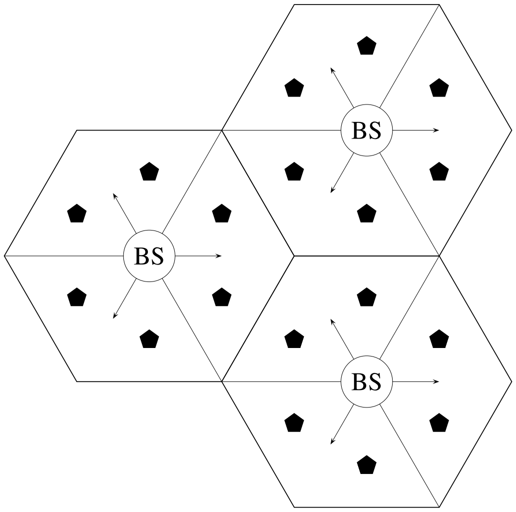
Our evaluation uses typical parameters of a mobile communications system; consider the hexagonal cell layout shown in Fig. 4(a), where one *site* hosts three base stations serving three adjacent *cells* (the arrows indicate the antenna lobe direction in each cell). Furthermore, we place relay nodes (indicated by pentagons) in such a way that we achieve a regular distribution of radio access points. Although this might not be optimal, it seems to be an intuitive choice as the power distribution over space becomes more homogeneous.

In such a system, different interference scenarios occur. This paper concentrates on the two particular situations illustrated in Fig. 4(b). Region $\boldsymbol{A}$ regards *inter-site interference* between two physically separated sites which are connected by a limited backhaul. Region $\boldsymbol{B}$ regards the *inter-cell (intra-site) interference* between two adjacent cells served at the same physical site and hence an (almost) unlimited backhaul is available. Section V presents results for both regions using the channel parameters developed by the European research project WINNER [8]. We assume a Gaussian channel model (no fading) and the pathloss and geometry parameters of [8] to reflect realistic interference situations.

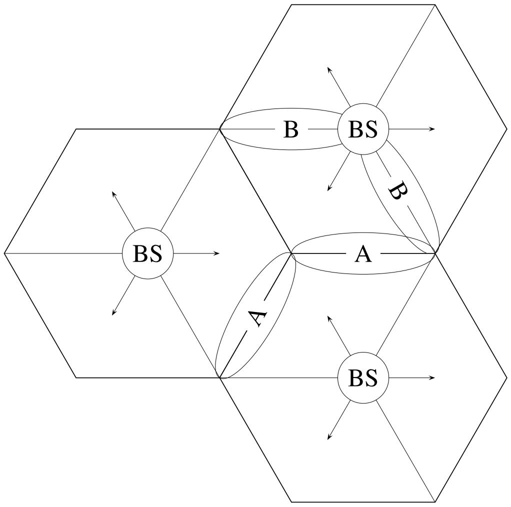
V. NUMERICAL RESULTS

In this section, we present numerical results for the protocols discussed in Section III. These protocols use standard techniques such as DPC with LQ precoding [9] and a simplified HK coding as proposed in [10]. We further compare these protocols to the reference case of $N = 0$ (no relays) and present results for direct transmission with resource coordination, HK coding without time sharing, and distributed DPC using an unlimited backhaul and perfect CSI at both transmitters.

Our analysis aims at showing which protocol is able to achieve sufficient performance while reducing protocol and scheduling complexity. For this purpose, we consider two scenarios modeling the case of inter-site and inter-cell in-



(a) Relay deployment

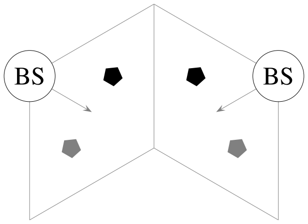


(b) Interesting regions

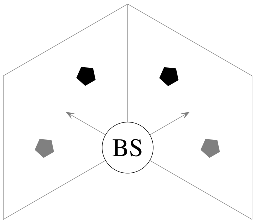
Fig. 4. Typical hexagonal cell layout of a mobile communications system. BS indicates one physical site which hosts three base stations serving the three adjacent cells. Pentagons indicate the deployed relay nodes.

terference, respectively. To analyze the inter-site interference scenario, we consider two base stations at adjacent sites and two relay nodes uniformly placed in between them (see Fig. 4(a)). The intra-site interference scenario uses two base stations at the same site which serve two adjacent cells. Furthermore, both relay nodes are placed at the cell edge (see Fig. 4(b)). Fig. 5(c) shows the symmetric setup used to evaluate the protocols in both scenarios. Two user terminals are symmetrically placed between both relays such that the distance between each relay and its assigned user is $\alpha \cdot d$ where d is the inter-relay distance and α is used to vary the user position. All results are presented for the downlink.

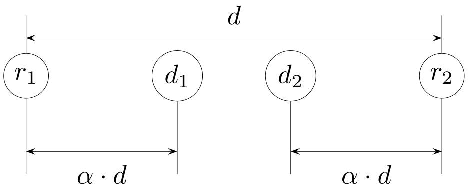
Fig. 6 and 7 show the relative performance improvement compared to direct transmission in terms of common rate of both user terminals for $\alpha \in [-0.4; 0.4]$. We see in Fig. 6 that for most values of α cooperative relaying achieves the best performance at the expense of a higher implementation



(a) Node placement in case of inter-site setup



(b) Node placement in case of intra-site (inter-cell) setup



(c) Setup for analysis of Gaussian channel

Fig. 5. Setup for Gaussian analysis. The black pentagon indicate the used relay nodes in the respective setups.

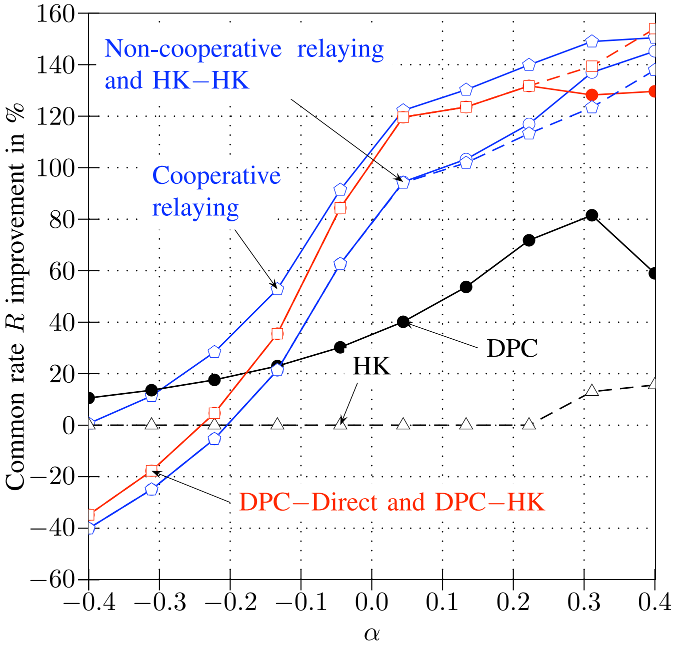


Fig. 6. Common rate performance improvement in case of the inter-site interference scenario. Dashed lines indicate that HK is used for $\mathcal{R} \rightarrow \mathcal{D}$ and solid lines in case of direct transmission.

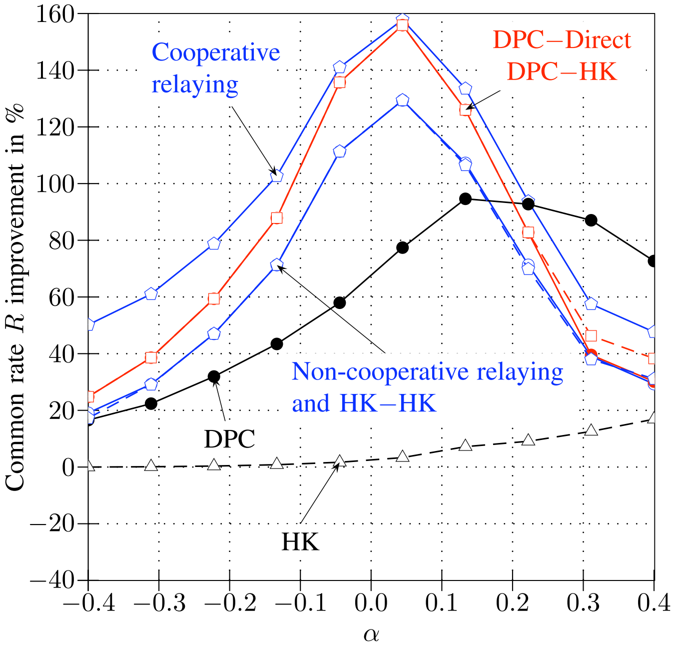


Fig. 7. Common rate performance improvement in case of the intra-site interference scenario. Dashed lines indicate that HK is used for $\mathcal{R} \rightarrow \mathcal{D}$ and solid lines in case of direct transmission.

complexity. Both protocols where DPC is used to serve the relay nodes achieve almost the same performance as cooperative relaying for large values of α. Using HK coding on the relay to user link further improves the achievable rates over direct transmission between relays and users. For small values of α, both variants perform insufficiently as the user terminals have a good connection towards the base stations and should be served directly (which is exploited by cooperative relaying). Non-cooperative relaying performs close to the former protocols for $\alpha \rightarrow 0.4$ but not for lower values. Besides, it outperforms the case when HK coding is used in both stages. This is due to the fact that in non-cooperative relaying both relay nodes and base stations are alternately transmitting. We further observe that DPC can only outperform the other protocols for small values of α and HK coding is only beneficial for $\alpha \rightarrow 0.4$.

The second scenario, which models the intra-site interference case and is shown in Fig. 7, draws almost the same picture. We see a major performance improvement as $\alpha \rightarrow 0$ which is due to the short distance between relay and user. The reason that DPC provides a higher performance benefit at $\alpha \rightarrow 0.4$ results from the short distance between both users and hence the increased interference. In case of small values of α both users are well separated and DPC does not provide a major performance advantage. Finally, the setup shows the a large performance gain of HK for higher values of α and a small gain for small values of α, as expected from [11].

VI. CONCLUSIONS AND OUTLOOK

This paper presented different approaches for the relay-interference channel, and one of these approaches might be of particular interest for mobile communications systems: the case where DPC is used on the source to relay link and HK coding on the relay to destination link. Although it is outperformed by cooperative relaying, it appears to be an reasonable choice and offers a good performance-complexity tradeoff. Using distributed DPC significantly improves the feeder link which is the dedicated bottleneck in a relay network. Besides, joint base station transmission is simplified since fixed relay nodes are easier to group, the exchanged CSI between base stations is reduced, and the coherence time/frequency is higher towards relay terminals. Hence, employing distributed DPC to serve relays has the potential to significantly reduce the complexity and to make joint base station transmission feasible.

On the relay to user link we are able to mitigate the interference using HK coding. Among others, this simplifies the scheduling as it can be easier synchronized between individual micro-cells. Furthermore, on system level HK coding could be done based on the pathloss information which further reduces the signaling overhead.

Our analysis focused on the special case of two communication pairs ($S = 2$) each supported by one relay node ($N = 1$). An extension to an arbitrary number of communication pairs and relay nodes offers the possibility for more complex scenarios within the presented framework. Besides, a general formulation using a cascade of $N + 1$ channels allows for an optimization over a larger set of possible protocols as well as more complex constraints reflecting the structure and requirements of mobile communications systems.

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