An Interference Management Scheme using Partial CSI for Partially Connected Cellular Networks

Xiang Li*, Daniel Papsdorf†, Anja Klein† and Tobias Weber*
*Institute of Communications Engineering, University of Rostock, Richard-Wagner-Str. 31, 18119 Rostock, Germany
†Communications Engineering Lab, Technische Universität Darmstadt, Merckstrasse 25, 64283 Darmstadt, Germany
{xiang.li, tobias.weber}@uni-rostock.de, {d.papsdorf, a.klein}@nt.tu-darmstadt.de

***Abstract*—We consider a partially connected cellular network where amplify-and-forward relays are deployed in order to help the cell-edge users to suppress the inter-cell interference in the downlink transmission. The one-way relaying protocol is employed. An interference management scheme for the considered cellular network using only partial channel state information is proposed. We show that interference-free transmissions can be achieved in the entire network using the proposed scheme. Furthermore, the feasibility conditions for the proposed scheme is discussed. The case where each relay has an individual power constraint is considered in order to find an interference-nulling solution. The simulation results show that the proposed scheme is able to achieve an outstanding performance, especially if the network is sparse.**

I. Introduction

In future cellular networks, relays can be deployed not only for conventional purposes like coverage extension [1], but also for interference management [2]. In particular, exploiting relays to suppress the inter-cell interference is of practical interest. To this purpose, a promising and practicable technique is relay-aided interference alignment (IA). Unlike IA without relays, it has been shown in literature that relay-aided IA requires only few antennas at the transmitters and the receivers, and that it has closed form solutions [3]. However, an obvious drawback of relay-aided IA, which is the same as for most of the conventional IA schemes, is the requirement of full channel state information (CSI). That is to say, every transmitter, every receiver, and every relay must be aware of all the channels in the entire network, which results in a severe signaling overhead. Consequently, recent research focuses on IA schemes without full CSI [4], [5], or even with no CSI at all [6], [7]. In our preliminary work [8], an IA scheme using partial CSI has been introduced, where the considered network consists of multiple partially connected subnetworks and we have shown that perfect IA is achievable even if every node is only aware of part of the channels. In the current work, we consider a partially connected cellular network where amplify-and-forward relays are deployed in order to help the cell-edge users to suppress the inter-cell interference in the downlink transmission. The one-way relaying protocol is employed. Each relay is assumed to be able to receive signals from multiple base stations (BSs) and forward the linearly processed signals to the mobile stations (MSs) close to the relay. The challenge is that a relay may also receive the signals which are not intended for the nearby MSs. How to nullify the interferences received by the relays, especially if full CSI is not available, has not been considered yet. Our contribution is to design a scheme to achieve interference-free transmission in the entire network using only partial CSI.

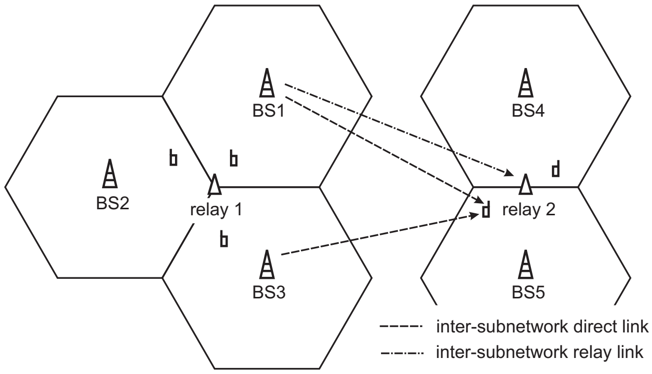

Fig. 1. An example of the considered networks. Two inter-subnetwork direct links and an inter-subnetwork relay link are present between the two subnetworks. The intra-subnetwork links are not depicted.

II. System Model

We consider the downlink transmission in a cellular network consisting of K cells. Let the K cells be divided into Q disjoint subsets such that the q-th subset includes K_q adjacent cells. In the q-th subset of the cells, a half-duplex amplify-and-forward relay equipped with N_q antennas is deployed to help the nearby MSs to suppress the inter-cell interference. We assume that in each cell, a single MS equipped with one antenna is located close to the relay and the BS uses a single antenna to serve the MS. To facilitate the discussions, we refer to the K_q BS-MS pairs along with the q-th relay as a subnetwork in the following of this paper.

Due to path losses, such a network typically can be considered as partially connected. In particular, we assume that each subnetwork is fully connected, i.e., the q-th relay is connected to all the K_q BSs and MSs in the q-th subnetwork and each one of the MSs directly receives signals from all the K_q BSs in the subnetwork. Furthermore, the relay and some of the MSs in a subnetwork may also receive interference from a few BSs in the other subnetworks, which will be referred to as inter-subnetwork interferences. However, the relay in one subnetwork is assumed not to interfere with the MSs in the other subnetwork. Fig. 1 shows an example of the considered cellular networks, where relay 1 and the three cells close to it form a subnetwork, while the other two cells and relay 2 form another subnetwork. Two inter-subnetwork direct links and an inter-subnetwork relay link are depicted in the figure.

A synchronized two-hop transmission scheme is applied incorporating the idea of relay-aided IA. In the first time slot, each BS transmits a single data symbol to the connected relays and MSs. Every relay will then forward a linearly processed signal to the connected MSs in the second time slot while the BSs transmit again to the connected MSs. The channels are assumed to remain constant throughout the transmission. We must point out that in some special cases, the considered two-hop transmission scheme does not require the deployment of relays to achieve interference-free transmission. For instance, if a subnetwork includes only one or two cells and the MSs in the subnetwork do not receive any inter-subnetwork interference signal, the problem is trivial. To exclude these special cases, we assume that every subnetwork includes at least three cells.

The following notations will be used. The channel between the k-th BS and the j-th MS is denoted by the scalar $h_{\text{MB}}^{(j,k)}$. The channel between the k-th MS and the q-th relay is denoted by the $N_q \times 1$ vector $\mathbf{h}_{\text{RB}}^{(q,k)}$. Finally, the channel between the q-th relay and the j-th MS is denoted by the $1 \times N_q$ vector $\mathbf{h}_{\text{MR}}^{(j,q)}$. The channel coefficients of the absent links are set to zero. The channel coefficients of the present links are assumed to be independently drawn from a Gaussian distribution. Furthermore, the transmit filter at the k-th BS and the receive filter at the j-th MS are denoted by $(v_1^{(k)}, v_2^{(k)})^{\text{T}}$ and $(u_1^{(j)}, u_2^{(j)})^{\text{T}}$, respectively. The processing matrix at the q-th relay is denoted by the $N_q \times N_q$ matrix $\mathbf{G}^{(q)}$.

We aim to nullify all the interferences in the entire network, i.e., the transmit filters at the BSs, the receive filters at the MSs, and the relay processing matrices shall be designed such that for any $k \neq j$, the interference-nulling condition

$$\left(u_1^{(j)*}, u_2^{(j)*}\right) \begin{pmatrix} h_{\text{MB}}^{(j,k)} & 0 \\ \mathbf{h}_{\text{MR}}^{(j,q)} \mathbf{G}^{(q)} \mathbf{h}_{\text{RB}}^{(q,k)} & h_{\text{MB}}^{(j,k)} \end{pmatrix} \begin{pmatrix} v_1^{(k)} \\ v_2^{(k)} \end{pmatrix} = 0 \tag{1}$$

is satisfied, where the j-th MS is assumed to belong to the q-th subnetwork. If the k-th BS also belongs to the q-th subnetwork, all the channel coefficients in (1) are non-zero with probability one and (1) corresponds to an intra-subnetwork interference-nulling condition. Otherwise, some of the channel coefficients may be zero depending on the network topology and (1) corresponds to an inter-subnetwork interference-nulling condition.

In order to solve (1), we introduce the quotients of the filter coefficients $v^{(k)} = v_2^{(k)}/v_1^{(k)}$ and $u^{(j)*} = u_1^{(j)*}/u_2^{(j)*}$, which specify the one-dimensional transmit signal subspace at a BS and the one-dimensional receive signal subspace at a MS, respectively. Using $v^{(k)}$ and $u^{(j)*}$, (1) can be linearized as

$$\mathbf{h}_{\text{MR}}^{(j,q)} \mathbf{G}^{(q)} \mathbf{h}_{\text{RB}}^{(q,k)} + h_{\text{MB}}^{(j,k)} \left(v^{(k)} + u^{(j)*}\right) = 0, \tag{2}$$

where the quotients of the filter coefficients $v^{(k)}$, $u^{(j)*}$, and the elements of $\mathbf{G}^{(q)}$ are the unknowns. A proper choice of the unknowns for all the BSs, MSs, and relays which satisfies (2) for all interference links is referred to as an interference-nulling solution. Note that not all the interference-nulling solutions ensure that the useful signals can be successfully transmitted to the intended MSs, as shown in [9]. This aspect will be further discussed in the full paper.

In this paper, we focus on using only partial CSI. More specifically, we assume that the BSs, the MSs, and the relay in a subnetwork know the channel coefficients in their own subnetwork. In addition to that, each relay has the receiver side CSI of the channels between itself and the connected BSs. Furthermore, the network topology is known to all the BSs, the MSs, and the relays. Using this particular type of channel knowledge, our scheme is able to solve the interference-nulling problem in the entire network.

III. Main Results

We first propose an interference management scheme using partial CSI for the considered cellular network based on the IA scheme proposed in [8]. Note that for inter-subnetwork interferences, the interference-nulling condition of (2) may have the following forms depending on the topology of the network.

- If the k-th BS is connected to both the j-th MS and the q-th relay, all channel coefficients in (2) are non-zero with probability one.
- If the k-th BS is directly connected to the j-th MS, but not connected to the q-th relay, (2) can be simplified as
$$v^{(k)} + u^{(j)*} = 0, \tag{3}$$
which suggests that the interference propagating via the inter-subnetwork direct link can be nullified by choosing orthogonal transmit and receive filters at the corresponding BS and MS without knowing the channel coefficient of the inter-subnetwork direct link.
- If the k-th BS is connected to the q-th relay, but not connected to the j-th MS, (2) can be rewritten as
$$\mathbf{h}_{\text{MR}}^{(j,q)} \mathbf{G}^{(q)} \mathbf{h}_{\text{RB}}^{(q,k)} = 0, \tag{4}$$
which suggests that the interference propagating via the inter-subnetwork relay link shall be forwarded in the null space of the channel $\mathbf{h}_{\text{MR}}^{(j,q)}$ by properly designing the relay processing matrix.
- Of course, if the BS is neither connected to the relay nor to the MS, (2) is an identity.

However, since only partial CSI is available, i.e., the channel coefficient $h_{\text{MB}}^{(j,k)}$ is unknown to the BSs, MSs, and the relay in the q-th subnetwork, the only way to nullify the inter-subnetwork interference between the k-th BS and the j-th MS is as follows. Firstly, the q-th relay chooses its processing matrix such that the interference received by the relay will not be forwarded to the j-th MS as given in (4). Secondly, the j-th MS chooses its receive filter orthogonal to the transmit filter at the k-th BS as given in (3). This strategy ensures that the inter-subnetwork interference can be nullified even without knowing the channel coefficient $h_{\text{MB}}^{(j,k)}$.

In the strategy described above, the j-th MS needs to know the filter coefficient $v^{(k)}$, which represents the one-dimensional transmit signal subspace at the k-th BS. To this end, a scheme based the one proposed in [8] is applied. Shortly speaking, Q steps are required to compute the interference-nulling solution for the entire network. In each step, one of the Q subnetworks will use the available CSI to determine a solution which

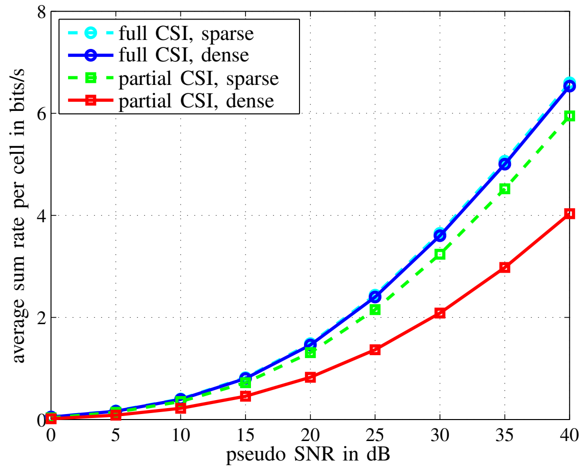

Fig. 2. Average sum rate per cell as a function of pseudo SNR

is able to nullify the intra-subnetwork interferences. Unlike [8], the relay shall also nullify the received inter-subnetwork interferences in the current paper. Afterwards, the subnetwork forwards some of its filter coefficients as side information to other subnetworks. Furthermore, depending on the network topology, the proposed scheme may also be parallelized to reduce the number of steps required, and therefore, to reduce the delay. The details of this scheme will be further introduced in the full paper. We also investigate the feasibility conditions for the considered scheme. The feasibility conditions will be derived by modelling the inter-subnetwork links as a graph. In a network with known topology, the required number of relay antennas will be given. For a fixed number of relay antennas, we derive an upper bound and a lower bound of the number of MSs that the relay is able to serve.

Once the interference-nulling problem is solved, i.e., the quotients $v^{(k)}$, $u^{(j)*}$, and the relay processing matrices $\mathbf{G}^{(q)}$ are found, one shall construct the transmit and receive filters $(v_1^{(k)}, v_2^{(k)})^{\mathrm{T}}$ and $(u_1^{(j)}, u_2^{(j)})^{\mathrm{T}}$ based on the solution. In the full paper, we will discuss two ways to construct the filters depending on the power constraints. Firstly, under a sum power constraint for each subnetwork, a water-filling solution will be used to deliver optimum performance. Secondly, under more practical assumptions, i.e., each relay has an individual power constraint, the choice of the transmit filters at the BSs will also be discussed.

IV. Simulations

In the full paper, the performance of the considered scheme will be shown by simulation results. In Fig. 2, the average sum rate per cell achieved using the considered scheme in a 9-cell scenario is illustrated. As compared to the IA scheme using full CSI, the proposed scheme is able to achieve the same degrees of freedom with only partial CSI. More simulation results and details will be discussed in the full paper.

V. Conclusion

To conclude, we propose an interference management scheme for the considered cellular network to suppress inter-cell interferences using only partial CSI based on the IA scheme proposed in [8]. Half-duplex relays are deployed in the scenario to help suppressing interferences for the nearby MSs. Taking the nature of cellular networks into account, we also consider the inter-subnetwork interferences at the relays. We show that interference-free transmissions can be achieved in the entire network using the proposed scheme. Furthermore, the feasibility conditions for the proposed scheme is discussed.

References

[1] R. Pabst, B. Walke, D. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. Falconer, and G. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Communications Magazine*, vol. 42, no. 9, pp. 80–89, Sep. 2004.

[2] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, pp. 379 –389, Feb. 2007.

[3] B. Nourani, S. A. Motahari, and A. K. Khandani, "Relay-aided interference alignment for the quasi-static interference channel," in *Proc. IEEE International Symposium on Information Theory*, Austin, USA, June 2010, pp. 405–409.

[4] S. Jafar, "Topological interference management through index coding," *IEEE Transactions on Information Theory*, vol. 60, no. 1, pp. 529–568, Jan. 2014.

[5] M. Maddah-Ali and D. Tse, "Completely stale transmitter channel state information is still very useful," *IEEE Transactions on Information Theory*, vol. 58, no. 7, pp. 4418–4431, July 2012.

[6] T. Gou, C. Wang, and S. Jafar, "Aiming perfectly in the dark-blind interference alignment through staggered antenna switching," *IEEE Transactions on Signal Processing*, vol. 59, no. 6, pp. 2734–2744, June 2011.

[7] S. Jafar, "Blind interference alignment," *IEEE Journal of Selected Topics in Signal Processing*, vol. 6, no. 3, pp. 216–227, 2012.

[8] X. Li, D. Papsdorf, A. Klein, and T. Weber, "An interference alignment scheme using partial CSI for large partially connected relay networks," in *Proc. IEEE 12th International Symposium on Wireless Communications Systems*, Brussels, Aug. 2015.

[9] X. Li, H. Al-Shatri, R. S. Ganesan, A. Klein, and T. Weber, "Feasibility conditions for relay-aided interference alignment in partially connected networks," in *Proc. IEEE 77th Vehicular Technology Conference*, Dresden, Germany, June 2013, pp. 1–5.