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Hybrid one-/two-way transmission scheme for bidirectional multi-user relaying under asymmetric rate requirements

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Abstract— **A single cell scenario consisting of a multi-antenna base station and several single antenna mobile stations is considered. An intermediate non-regenerative multi-antenna relay station is used to support the bidirectional communications. In such a scenario, the required data rates for up- and downlink are typically different which is considered by introducing asymmetric rate requirements. A transmission via multiple orthogonal subcarriers as used in OFDM is investigated and a hybrid one-/two-way transmission scheme per subcarrier is proposed to increase the achievable sum rates under the asymmetric rate requirements. To handle the asymmetric rate requirements at the relay station, a weighted self-interference aware relay transceive filter per subcarrier is applied. Furthermore, different transmit and receive filter strategies at the base station are investigated. Performance results show that higher sum rates can be achieved with the hybrid one-/two-way relaying scheme than via a pure two-way relaying scheme.**

I. Introduction

In wireless systems, relay stations can be used to support or enable the communications between nodes. In this paper, non-regenerative multi-antenna relaying in a multi-user scenario is investigated. The bidirectional communications between a multi-antenna base station BS and several single antenna mobile stations are performed via an intermediate non-regenerative multi-antenna relay station RS. To overcome the duplexing loss of conventional relaying schemes, the well-known two-way relaying protocol of [1] can be applied to enable the bidirectional communications between BS and the mobile stations [2]–[5].

Non-regenerative multi-antenna two-way relaying in a single-pair scenario is investigated in [6]–[8] and multi-pair two-way relaying with single-antenna nodes and a multi-antenna relay has been considered in [9]–[11]. The authors of [12]–[14] investigate multi-pair two-way relaying with multi-antenna nodes. Typically, more or less symmetric data rates for the bidirectional communications are achieved in non-regenerative two-way relaying. However, for many practical applications the required data rates in downlink are higher than the required data rates in uplink. In one of our previous works [5], such asymmetric rate requirements between up- and downlink are considered for a multi-user single cell scenario by introducing a weighted self-interference aware relay transceive filter. However, solely the transmission via a single carrier is considered and pure two-way relaying is performed at RS.

In this paper, a hybrid one-/two-way relaying scheme for the transmission via multiple orthogonal subcarriers is proposed which is designed to achieve higher downlink than uplink data rates. The proposed scheme utilizes the spatial resource allocation over the subcarriers to increase the achievable data rates under the asymmetric rate requirements by combining two-way relaying with unidirectional one-way relaying on each subcarrier. The weighted self-interference aware relay transceive filter of [5] is applied and different transmit and receive filter designs at BS are investigated. Furthermore, a suboptimal low-complexity approach for optimizing the transmission via multiple orthogonal subcarriers under asymmetric rate requirements is presented.

The paper is organized as follows. In Section II, the system model is given and in Section III, the different considered subproblems are described. The hybrid one-/two-way transmission scheme is introduced in Section IV. In Section V, the relay transceive filter design and the transmit and receive filter design at the base station as well as the optimization of the transmit powers of the mobile stations are described. Performance results are presented in Section VI and Section VII concludes the paper.

Throughout this paper, boldface lower case and upper case letters denote vectors and matrices, respectively, while normal letters denote scalar values. The superscripts $(\cdot)^{\mathrm{T}}$, $(\cdot)^*$ and $(\cdot)^{\mathrm{H}}$ stand for matrix or vector transpose, complex conjugate and complex conjugate transpose, respectively. The operators $\mathrm{tr}(\cdot)$, $\otimes$ denote the sum of the main diagonal elements of a matrix and the Kronecker product of matrices, respectively. The operators $\Re[\cdot]$ and $||\cdot||_2$ denote the real part of a scalar and the Frobenius norm of a matrix, respectively. The matrix vectorization operator $\mathrm{vec}(Z)$ stacks the columns of matrix Z into a vector. The operator $\mathrm{vec}^{-1}_{M,N}(\cdot)$ is the revision of the operator $\mathrm{vec}(\cdot)$, i.e., a vector of length MN is sequentially divided into N vectors of length M which are combined to a matrix with M rows and N columns. The operator $\mathrm{mod}_y x$ returns the modulus of x after division by y and $\mathbf{I}_M$ denotes an identity matrix of size $M \times M$.

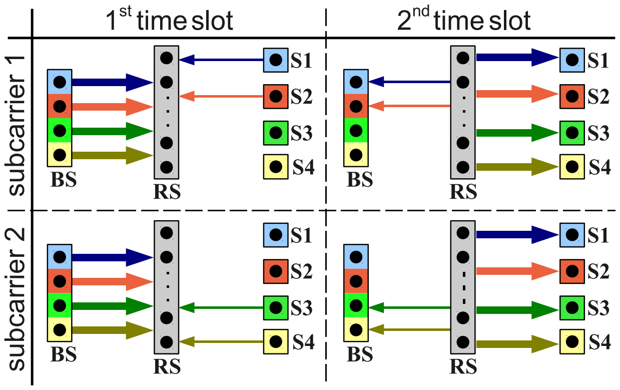

Fig. 1. Example of multi-user hybrid one-/two-way relaying for $K = 4$ mobile stations and $T = 2$ subcarriers.

II. System model

Bidirectional multi-antenna two-hop relaying for a multi-user multi-carrier scenario consisting of a multi-antenna base station and several single antenna mobile stations as shown in Figure 1 is considered. Furthermore, it is assumed that the instantaneous data rates in downlink from BS to each mobile station are required to be equal and are required to be r times the instantaneous data rates in uplink from each mobile station to BS, $r > 0$, which is illustrated by the thickness of the arrows in Figure 1. The considered system model is an extension of the system model presented in [5] to a general multi-carrier multi-user scenario.

The bidirectional communications between the half-duplex base station BS and K half-duplex mobile stations S_k, $k = 1, 2, ...K$, are performed via an intermediate half-duplex relay station RS via T orthogonal subcarriers. In the first time slot, BS and part of the mobile stations are simultaneously transmitting to RS on each subcarrier as exemplarly shown in Figure 1 for a scenario with $T = 2$ subcarriers. In the second time slot, RS retransmits a linearly processed version of the received signals towards BS and the mobile stations. This scheme is termed multi-user hybrid one-/two-way relaying and is introduced in more detail in Section IV. BS is equipped with $M = K$ antennas and the number of antennas at RS is given by $L \geq K$. The transmit power at BS, at each mobile station and at RS is limited on each subcarrier by $P_{\mathrm{BS,max}}$, $P_{\mathrm{MS,max}}$ and $P_{\mathrm{RS,max}}$, respectively.

The system equations for hybrid one-/two-way relaying on subcarrier t, $t = 1, 2, ..., T$, are presented in the following. The channels $\mathbf{H}_{\mathrm{BS},t} \in \mathbb{C}^{L\times M}$ and $\mathbf{h}_{k,t} \in \mathbb{C}^{L\times 1}$ from BS to RS and from S_k to RS, respectively, are assumed to be constant during one transmission cycle of the hybrid one-/two-way scheme and channel reciprocity is assumed. All signals are assumed to be statistically independent and the noise at RS and at the nodes is assumed to be additive white Gaussian with variances $\sigma^2_{\mathrm{n,RS}}$ and σ^2_{n} on each subcarrier, respectively. The transmitted symbols of BS and S_k are contained in $\mathbf{x}_{\mathrm{BS},t}$ and $x_{\mathrm{S}_k,t}$, respectively. Using the transmit filter $\mathbf{Q}_{\mathrm{BS},t}$,$||\mathbf{Q}_{\mathrm{BS},t}||_2^2 = P_{\mathrm{BS,max}}$, at BS and the transmit power $P_{\mathrm{S}_k,t} \leq P_{\mathrm{MS,max}}$ at S_k, the received baseband signal at RS on subcarrier t in the first time slot is given by

$$\mathbf{y}_{\mathrm{RS},t} = \mathbf{H}_{\mathrm{BS},t}\mathbf{Q}_{\mathrm{BS},t}\mathbf{x}_{\mathrm{BS},t} + \sum_{k=1}^{K} \mathbf{h}_{k,t}\sqrt{P_{\mathrm{S}_k,t}}x_{\mathrm{S}_k,t} + \mathbf{n}_{\mathrm{RS},t}, \tag{1}$$

where $\mathbf{n}_{\mathrm{RS},t}$ represents the complex white Gaussian noise vector at RS. If a mobile station S_k does not transmit on subcarrier t, the transmit power of this mobile station on subcarrier t is given by $P_{\mathrm{S}_k,t} = 0$. RS linearly processes the received signal and the transceive filter at RS is given by

$$\mathbf{G}_t = \gamma\widetilde{\mathbf{G}}_t, \tag{2}$$

where $\widetilde{\mathbf{G}}_t$ is the transceive filter at RS which does not implicitly fulfill the power constraint and γ is a scalar value to satisfy the relay power constraint. γ is given by

$$\gamma = \sqrt{\frac{P_{\mathrm{RS,max}}}{P_{\mathrm{RS},t}}}, \tag{3}$$

with

$$P_{\mathrm{RS},t} = ||\widetilde{\mathbf{G}}_t\mathbf{H}_{\mathrm{BS},t}\mathbf{Q}_{\mathrm{BS},t}||_2^2 + \sum_{k=1}^{K} ||\widetilde{\mathbf{G}}_t\mathbf{h}_{k,t}||_2^2 P_{\mathrm{S}_k,t} + ||\widetilde{\mathbf{G}}_t||_2^2\sigma^2_{\mathrm{n,RS}}, \tag{4}$$

the transmit power at RS in case of using $\widetilde{\mathbf{G}}_t$ for the retransmission of the received signals. In the second time slot, the relay retransmits a linearly processed version of $\mathbf{y}_{\mathrm{RS}}$ to all nodes. The received signals $\mathbf{y}_{\mathrm{BS},t}$ and $y_{\mathrm{S}_k,t}$ using the receive filters $\mathbf{D}_{\mathrm{BS},t}$ and $d_{k,t}$ at BS and S_k, respectively, are given by

$$\mathbf{y}_{\mathrm{BS},t} = \mathbf{D}_{\mathrm{BS},t}(\mathbf{H}^{\mathrm{T}}_{\mathrm{BS},t}\mathbf{G}_t\mathbf{y}_{\mathrm{RS},t} + \mathbf{n}_{\mathrm{BS},t}), \tag{5a}$$

$$y_{\mathrm{S}_k,t} = d_{k,t}(\mathbf{h}^{\mathrm{T}}_{k,t}\mathbf{G}_t\mathbf{y}_{\mathrm{RS},t} + n_{k,t}), \tag{5b}$$

where $\mathbf{n}_{\mathrm{BS},t}$ and $n_{k,t}$ represent the complex white Gaussian noise at BS and S_k, respectively. BS receives the useful signals from all transmitting mobile stations on subcarrier t, receives back-propagated self-interference and noise. Each mobile station receives its intended useful signal, receives interference from the signals intended for the other mobile stations, termed "BS-MS-interference", receives interference from the signals transmitted by the other mobile stations which are retransmitted by RS, termed "MS-MS-interference", and receives back-propagated self-interference as well as noise.

RS is assumed to have perfect global channel state information (CSI). BS is assumed to have perfect CSI of the overall channels

$$\mathbf{H}_{\mathrm{Tx},t} = [(\mathbf{h}^{\mathrm{T}}_{1,t}\mathbf{G}_t\mathbf{H}_{\mathrm{BS},t})^{\mathrm{T}}, ..., (\mathbf{h}^{\mathrm{T}}_{K}\mathbf{G}_t\mathbf{H}_{\mathrm{BS},t})^{\mathrm{T}}]^{\mathrm{T}}, \tag{6a}$$

$$\mathbf{H}_{\mathrm{Rx},t} = \mathbf{H}^{\mathrm{T}}_{\mathrm{BS},t}\mathbf{G}_t[\mathbf{h}_{1,t}\sqrt{P_{\mathrm{S}_1,t}}, ..., \mathbf{h}_{K,t}\sqrt{P_{\mathrm{S}_K,t}}], \tag{6b}$$

from BS to the mobile stations and vice versa, respectively, as well as of the back-propagation channels $\mathbf{H}_{\mathrm{CDI},t} = \mathbf{H}^{\mathrm{T}}_{\mathrm{BS},t}\mathbf{G}_t\mathbf{H}_{\mathrm{BS},t}, \forall t$. Each mobile station S_k

is assumed to have perfect receive CSI of the overall channels from BS to S_k

$$\mathbf{h}_{\mathrm{Rx},k,t} = \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G}_t \mathbf{H}_{\mathrm{BS},t} \mathbf{q}_{\mathrm{BS},k,t}, \tag{7}$$

where $\mathbf{q}_{\mathrm{BS},k,t}$ is the k-th column vector of $\mathbf{Q}_{\mathrm{BS},t}$ and of the back-propagation channels $\mathbf{h}_{\mathrm{CDI},k,t} = \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G}_t \mathbf{h}_{k,t}$, $\forall t$. Furthermore, it is assumed that BS and the mobile stations can perfectly subtract the back-propagated self-interferences. Thus, the "MS-MS-interference" as well as the "BS-MS-interference" have to be suppressed by the relay transceive filter and the back-propagated self-interference can be subtracted at the nodes [1].

Let us define the vector $\mathbf{a}_{k,t} = \mathbf{d}_{\mathrm{BS},k,t} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{T}} \mathbf{G}_t$, where $\mathbf{d}_{\mathrm{BS},k,t}$ is the kth row vector of $\mathbf{D}_{\mathrm{BS},t}$. Thus, the expected signal, interference and noise powers for the transmission from S_k to BS on subcarrier t after self-interference cancellation are given by

$$P_{\mathrm{S}}^{\mathrm{S}_k,t} = \mathbf{a}_{k,t} \mathbf{h}_{k,t} P_{\mathrm{S}_k,t} \mathbf{h}_{k,t}^{\mathrm{H}} \mathbf{a}_{k,t}^{\mathrm{H}}, \tag{8a}$$

$$P_{\mathrm{I}}^{\mathrm{S}_k,t} = \sum_{j=1, j\neq k}^{K} \mathbf{a}_{k,t} \mathbf{h}_{j,t} P_{\mathrm{S}_j,t} \mathbf{h}_{j,t}^{\mathrm{H}} \mathbf{a}_{k,t}^{\mathrm{H}}, \tag{8b}$$

$$P_{\mathrm{N}}^{\mathrm{S}_k,t} = \mathbf{a}_{k,t} \mathbf{a}_{k,t}^{\mathrm{H}} \sigma_{n,\mathrm{RS}}^2 + \mathbf{d}_{\mathrm{BS},k,t} \mathbf{d}_{\mathrm{BS},k,t}^{\mathrm{H}} \sigma_{\mathrm{n}}^2, \tag{8c}$$

respectively. The signal, interference and noise powers after self-interference cancellation for the transmission from BS to S_k are given by

$$P_{\mathrm{S}}^{\mathrm{BS}_k,t} = \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G}_t \mathbf{H}_{\mathrm{BS},t} \mathbf{q}_{\mathrm{BS},k,t} \mathbf{q}_{\mathrm{BS},k,t}^{\mathrm{H}} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{H}} \mathbf{G}_t^{\mathrm{H}} \mathbf{h}_{k,t}^{*}, \tag{9a}$$

$$\begin{aligned} P_{\mathrm{I}}^{\mathrm{BS}_k,t} = {} & \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G}_t \mathbf{H}_{\mathrm{BS},t} \mathbf{Q}_{\mathrm{BS},t} \mathbf{Q}_{\mathrm{BS},t}^{\mathrm{H}} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{H}} \mathbf{G}_t^{\mathrm{H}} \mathbf{h}_{k,t}^{*} \\ & + \sum_{j=1, j\neq k}^{K} \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G}_t \mathbf{h}_{j,t} P_{\mathrm{S}_j,t} \mathbf{h}_{j,t}^{\mathrm{H}} \mathbf{h}_{k,t}^{*} \mathbf{G}_t^{\mathrm{H}} - P_{\mathrm{S}}^{\mathrm{BS}_k,t}, \end{aligned} \tag{9b}$$

$$P_{\mathrm{N}}^{\mathrm{BS}_k,t} = \mathbf{h}_{k,t}^{\mathrm{T}} \mathbf{G} \mathbf{G}^{\mathrm{H}} \mathbf{h}_{k,t}^{*} \sigma_{n,\mathrm{RS}}^2 + \sigma_{\mathrm{n}}^2, \tag{9c}$$

respectively. Assuming that Gaussian codebooks are used for each data stream, the maximum achievable data rate from S_k to BS considering self-interference cancellation is given by

$$C_{\mathrm{S}_k} = \frac{1}{2} \sum_{t=1}^{T} \log_2(1 + P_{\mathrm{S}}^{\mathrm{S}_k,t} (P_{\mathrm{I}}^{\mathrm{S}_k,t} + P_{\mathrm{N}}^{\mathrm{S}_k,t})^{-1}), \tag{10}$$

and the achievable data rate from BS to S_k considering self-interference cancellation is given by

$$C_{\mathrm{BS}_k} = \frac{1}{2} \sum_{t=1}^{T} \log_2(1 + P_{\mathrm{S}}^{\mathrm{BS}_k,t} (P_{\mathrm{I}}^{\mathrm{BS}_k,t} + P_{\mathrm{N}}^{\mathrm{BS}_k,t})^{-1}), \tag{11}$$

In this paper, asymmetric data rate requirements are considered. As mentioned before, the instantaneous data rates in downlink from BS to each mobile station are required to be equal and are required to be r times the instantaneous data rates in uplink from each mobile station to BS, $r > 0$. Thus, r describes the ratio between C_{BS_k} and C_{S_k}. It is assumed that specific asymmetric rate requirements have to be fulfilled. Thus, the constraints

$$r = C_{\mathrm{BS}_k} / C_{\mathrm{S}_k}, \forall k = 1, 2, ..., K, \tag{12a}$$

$$C_{\mathrm{BS}_k} = C_{\mathrm{BS}_l}, \forall k, l = 1, 2, ..., K, \tag{12b}$$

are considered for the sum rate maximization. Considering the constraint (12a), the achievable data rate between BS and S_k is given by $C_k = \min(C_{\mathrm{BS}_k}, rC_{\mathrm{S}_k})$ and the achievable data rate between S_k and BS is given by $\frac{1}{r} C_k$. Considering both constraints (12a) and (12b), the achievable sum rate under the asymmetric rate requirements is given by

$$C_{\mathrm{sum}} = K(1 + 1/r) \cdot \min_k C_k. \tag{13}$$

III. Subproblems for sum rate maximization

To maximize the sum rate C_{sum} of (13), the relay transceive filter, the transmit and receive filters at BS as well as the transmit powers of the mobile stations have to be optimized jointly on each subcarrier. Additionally, for the hybrid one-/two-way transmission scheme, it has to be determined on which subcarriers each mobile station has to transmit to maximize the achievable sum rate. To reduce the computational complexity, we propose a suboptimal low-complexity approach to perform the subcarrier allocation for the hybrid one-/two-way transmission scheme as described in Section IV. Furthermore, we propose to decouple the relay transceive filter design and the transmit and receive filter design at BS as well as the optimization of the mobile station transmit powers. Thus, the considered subproblems are:

- the subcarrier allocation for the hybrid one-/two-way transmission scheme treated in Section IV,
- the design of the relay transceive filter described in Section V-A,
- the design of the transmit (Tx) and receive (Rx) filters at BS treated in Section V-B,
- the optimization of mobile station transmit powers and the numerical optimization treated in Section V-C.

In Figure 2, the considered subproblems are illustrated. Firstly, each mobile station S_k transmits one data stream on each subcarrier using the transmit power $P_{\mathrm{S}_k,t} = P_{\mathrm{MS,max}}$, $\forall t$. Secondly, the relay transceive filter and the Tx and Rx filters at BS are determined as described in Section V-A and Section V-B, respectively, using $w_k = 1$, $\forall k$, as weighting parameters for the relay transceive filter. Additionally, the power distribution at BS is numerically optimized to fulfill the constraint (12b). Thirdly, the subcarrier allocation for the hybrid one-/two-way transmission scheme is performed which is described in Section IV. If the subcarrier allocation has changed, the relay transceive filter and the Tx and Rx filters at BS are recalculated. Thus, the optimization starts again from step two. Fourthly, if the subcarrier allocation has not changed in the previous step, the numerical optimization of the relay transceive filter is performed as described in Section

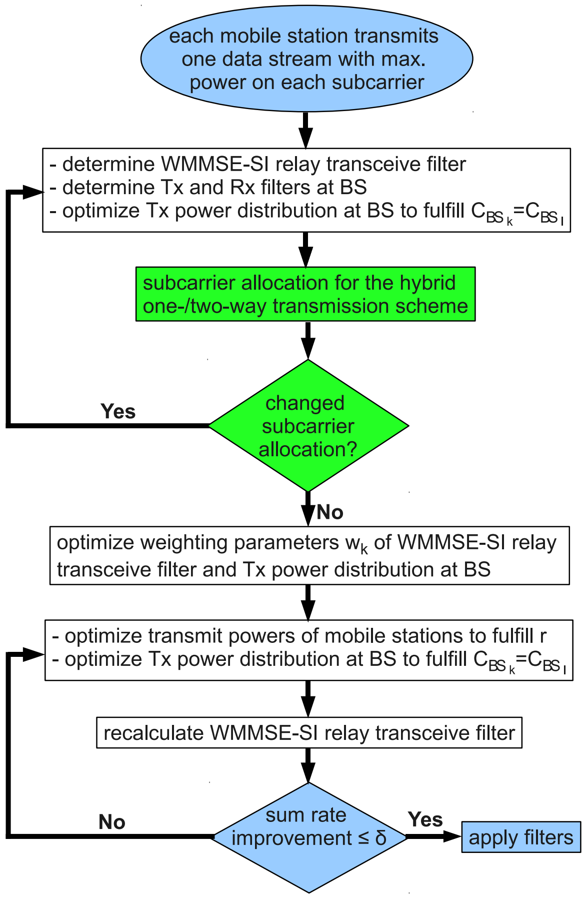

Fig. 2. Subproblems for sum rate maximization.

V-C. Fifthly, the transmit powers of the mobile stations and the transmit power distribution at BS are optimized to fulfill the constraints (12a) and (12b). Afterwards, an alternating optimization between the relay transceive filter and the transmit powers at the nodes as well as the transmit power distribution at BS is performed until convergence. The proposed optimization of the subproblems is a suboptimal approach for maximizing C_{sum}.

IV. Hybrid one-/two-way transmission scheme

In this section, the hybrid one-/two-way transmission scheme is introduced. Initially, each mobile station transmits on each subcarrier with maximum transmit power $P_{\mathrm{S}_k,t} = P_{\mathrm{MS,max}}$. This corresponds to pure multi-user two-way relaying and the achievable data rate from S_k to BS on subcarrier t is given by

$$C_{\mathrm{S}_k,t} = \frac{1}{2}\log_2(1 + P_{\mathrm{S}}^{\mathrm{S}_k,t}(P_{\mathrm{I}}^{\mathrm{S}_k,t} + P_{\mathrm{N}}^{\mathrm{S}_k,t})^{-1}). \quad (14)$$

The intention of the hybrid one-/two-way transmission scheme is to reduce the "MS-MS-interference" and to increase the achievable downlink data rates which are the limiting data rates in case of asymmetric rate requirements with $r > 1$. Therefore, only part of the subcarriers are allocated to each mobile station and the transmit powers of each mobile station are set to zero on the remaining subcarriers. The general subcarrier allocation for the hybrid one-/two-way transmission scheme is described in the following and afterwards the scheme is exemplarily described for a scenario with $K = 4$ mobile stations and $T = 2$ subcarriers.

Firstly, the subcarriers t on which S_k transmits with maximum power $P_{\mathrm{S}_k,t} = P_{\mathrm{MS,max}}$ are collected in the subset $\mathcal{T}_k$. Secondly, the subcarrier $t_{\min,k} \in \mathcal{T}_k$ on which S_k achieves the lowest data rate $C_{\mathrm{S}_k,t_{\min,k}} = \min_{t \in \mathcal{T}_k} C_{\mathrm{S}_k,t}$ is determined for each mobile station. Thirdly, it is computed if each mobile station S_k can fulfill constraint (12a) without transmitting on $t_{\min,k}$ by testing the following condition

$$C_{\mathrm{BS}_k} < r(C_{\mathrm{S}_k} - C_{\mathrm{S}_k,t_{\min,k}}), \forall k. \quad (15)$$

If the condition is fulfilled, the transmit power of S_k on subcarrier $t_{\min,k}$ is given by $P_{\mathrm{S}_k,t_{\min,k}} = 0$. Thus, the subcarrier $t_{\min,k}$ is no longer allocated to S_k. Fourthly, if the subcarrier allocation has changed for any mobile station, the relay transceive filter and the Tx and Rx filters at BS are recalculated and the subcarrier allocation process described above is repeated. Fifthly, it is computed if all mobile stations can still fulfill the constraint (12a) by testing the condition $C_{\mathrm{BS}_k} > rC_{\mathrm{S}_k}, \forall k$. If $C_{\mathrm{BS}_k} < rC_{\mathrm{S}_k}, \forall k$, the subcarrier allocation is finished. If $C_{\mathrm{BS}_k} > rC_{\mathrm{S}_k}$ is fulfilled for any mobile station S_k and not all subcarriers are allocated to S_k, the transmit powers of the mobile stations which have been set to zero during the previous iteration are reset to $P_{\mathrm{S}_k,t} = P_{\mathrm{MS,max}}$ and the subcarrier allocation is finished afterwards.

In the following, the proposed hybrid one-/two-way transmission scheme is exemplarily described for a scenario with $K = 4$ mobile stations, $T = 2$ subcarriers and for asymmetric rate requirements of $r \geq 2$. The overall bidirectional transmissions between BS and the mobile stations are performed in two time slots via both subcarriers as shown in Figure 1. In the first time slot, BS simultaneously transmits one data stream per mobile station on each subcarrier, but each mobile stations only transmits on one subcarrier, because the transmit powers of S_1 and S_2 are set to zero on subcarrier $t = 2$ and the transmit powers of S_3 and S_4 are set to zero on subcarrier $t = 1$ during the subcarrier allocation described in the previous paragraph. Thus, each mobile station only transmits one data stream. In the second time slot, RS retransmits a linearly processed version of the superimposed received signals back to the nodes. BS receives one data stream from each mobile station, receives back-propagated self-interference and noise. Each mobile station receives one data stream from BS per subcarrier, receives interferences from the signals intended for the other mobile stations, receives interferences from the signals transmitted by the other mobile stations which are retransmitted by RS, termed "MS-MS-interference", and receives back-propagated self-interference as well as noise. Before recovering the desired signals, BS and the mobile stations subtract the back-propagated self-interferences.

Thus, the hybrid one-/two-way transmission scheme performs unidirectional one-way relaying for half of the mobile stations on each subcarrier and two-way relaying for the other half of the mobile stations to achieve asymmetric rate requirements of $r \geq 2$. As shown in Section VI, higher sum rates compared to pure two-way relaying can be achieved because less signals are simultaneously transmitted to RS on each subcarrier which simplifies the spatial separation of the signals and therewith improves the interference suppression. Especially, "MS-MS-interference" is reduced and higher downlink data rates can be achieved.

V. Filter design

The maximization of the sum rate with respect to the joint design of the relay transceive filter and the transmit and receive filter at the base station is still non-convex. Thus, the design of these filters is decoupled and an alternating optimization is performed. Furthermore, the designs are based on minimizing the mean square error (MSE) to obtain convex problems and analytical solutions.

A. Relay transceive filter

In the following, a weighted self-interference aware MMSE relay transceive filter termed WMMSE-SI is presented which minimizes the weighted MSE on each subcarrier t for given transmit and receive filters at the BS. The derivation of the WMMSE-SI relay transceive filter for $K = 2$ multi-antenna mobile stations is given in [5]. In this paper, the WMMSE-SI filter of [5] is modified to handle K single antenna mobile stations. Thus, only some ideas of the filter design are presented in this paper and a repetition of the derivations is omitted. The capability of the nodes to perform self-interference cancellation is considered by the definition of the MSE equations. In these equations, the error caused by self-interference is removed so that back-propagated self-interference is only considered in the power constraint at RS and is not intentionally suppressed by the relay transceive filter. To consider the asymmetric rate requirements, the errors for each direction of transmission are separated and weighting parameters are introduced. In these equations, the transmitted symbols of BS which are intended for Sk are described by $x_{\mathrm{BS}k}$. The general equation for the relay transceive filter design subject to the transmit power constraint $P_{\mathrm{RS}} \leq P_{\mathrm{RS,max}}$ is given by

$$\mathbf{G}_t = \arg\min_{\mathbf{G}_t} \mathrm{E}\left\{ w_k \sum_{k=1}^{K} \left\| x_{\mathrm{BS},k,t} - \hat{x}_{\mathrm{BS},k,t} \right\|_2^2 \right\} + \mathrm{E}\left\{ \sum_{k=1}^{K} (2 - w_k) \left\| x_{\mathrm{S}_k,t} - \hat{x}_{\mathrm{S}_k,t} \right\|_2^2 \right\}, \tag{16}$$

where the parameters w_k, $0 \leq w_k \leq 2$ are used to weight the MSE for each direction of transmission and where $\hat{x}_{\mathrm{S}_k,t}$ and $\hat{x}_{\mathrm{BS},k,t}$ are the estimates of $x_{\mathrm{S}_k,t}$ and $x_{\mathrm{BS},k,t}$ at BS and S_k, respectively. The MSE of (16) in combination with the power constraint of RS results in a convex problem with respect to $\mathbf{G}_t$ for fixed transmit and receive filters at the nodes. This problem can be solved by using Lagrangian optimization. Let matrices $\boldsymbol{\Upsilon}_t^{(k)}$, $\boldsymbol{\Upsilon}_t^{(\mathrm{BS})}$ and $\boldsymbol{\Upsilon}_t$ be given by

$$\boldsymbol{\Upsilon}_t^{(k)} = \mathbf{h}_{k,t} P_{\mathrm{S}_k,t} \mathbf{h}_{k,t}^{\mathrm{H}} + \frac{1}{K} \sigma_{n,\mathrm{RS}}^2 \mathbf{I}_L, \tag{17a}$$

$$\boldsymbol{\Upsilon}_t^{(\mathrm{BS})} = \mathbf{H}_{\mathrm{BS,t}} \mathbf{Q}_{\mathrm{BS},t} \mathbf{R}_{\mathbf{x}_{\mathrm{BS},t}} \mathbf{Q}_{\mathrm{BS},t}^{\mathrm{H}} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{H}} + \sigma_{n,\mathrm{RS}}^2 \mathbf{I}_L, \tag{17b}$$

$$\boldsymbol{\Upsilon}_t = \mathbf{H}_{\mathrm{BS},t} \mathbf{Q}_{\mathrm{BS},t} \mathbf{R}_{\mathbf{x}_{\mathrm{BS},t}} \mathbf{Q}_{\mathrm{BS},t}^{\mathrm{H}} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{H}} + \sum_{k=1}^{K} \mathbf{h}_{k,t} P_{\mathrm{S}_k,t} \mathbf{h}_{k,t}^{\mathrm{H}} + \sigma_{n,\mathrm{RS}}^2 \mathbf{I}_L, \tag{17c}$$

with $\mathbf{R}_{\mathbf{x}_{\mathrm{BS},t}}$ the signal covariance matrices of $\mathbf{x}_{\mathrm{BS},t}$. Using these definitions, matrix $\mathbf{K}_t$ is defined as

$$\begin{aligned}
\mathbf{K}_t = &\sum_{k=1}^{K} w_k \left[\boldsymbol{\Upsilon}_t^{(\mathrm{BS})^{\mathrm{T}}} \otimes \left(\mathbf{h}_{k,t}^{*} \mathbf{h}_{k,t}^{\mathrm{T}} \right) \right] \\
&+ \sum_{k=1}^{K} w_k \sum_{l=1, l\neq k}^{K} \left[\boldsymbol{\Upsilon}_t^{(\mathrm{l})^{\mathrm{T}}} \otimes \left(\mathbf{h}_{k,t}^{*} \mathbf{h}_{k,t}^{\mathbf{T}} \right) \right] \\
&+ \sum_{k=1}^{K} \beta_k \sum_{l=1}^{K} \left[\boldsymbol{\Upsilon}_t^{(l)^{\mathrm{T}}} \otimes \left(\mathbf{H}_{\mathrm{BS},t}^{*} \mathbf{d}_{\mathrm{BS},k,t}^{\mathrm{H}} \mathbf{d}_{\mathrm{BS},k,t} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{T}} \right) \right] \\
&+ \left[\boldsymbol{\Upsilon}_t^{\mathrm{T}} \otimes \frac{2K\sigma_n^2}{P_{\mathrm{RS,max}}} \mathbf{I}_L \right],
\end{aligned} \tag{18}$$

with $\beta_k = 2 - w_k$.

Thus, using Eqs. (2), (3) and (18), the WMMSE-SI filter at RS which solves problem (16) is given by

$$\widetilde{\mathbf{G}}_t = \mathrm{vec}_{L,L}^{-1} \left(\mathbf{K}_t^{-1} \, \mathrm{vec} \left(\sum_{k=1}^{K} w_k \mathbf{h}_{k,t}^{*} \mathbf{q}_{\mathrm{BS},k,t}^{\mathrm{H}} \mathbf{H}_{\mathrm{BS},t}^{\mathrm{H}} + \sum_{k=1}^{K} (2 - w_k) \mathbf{H}_{\mathrm{BS},t}^{*} \mathbf{d}_{\mathrm{BS},k,t}^{\mathrm{H}} \mathbf{h}_{k,t}^{\mathrm{H}} \sqrt{P_{\mathrm{S}_k,t}} \right) \right). \tag{19}$$

The derived WMMSE-SI transceive filter at RS minimizes the weighted MSE for given transmit and receive filters at the nodes. Initially, the weighting parameters $w_k = 1$, $\forall k$ and the Tx and Rx filters at BS which are introduced in Section V-B are diagonal matrices as given in (20a) and (20b). Afterwards, the weighting factors w_k are determined by numerical optimization with respect to the asymmetric rate requirement as described in Section V-C. Furthermore, an alternating optimization between the WMMSE-SI relay transceive filter and the Tx and Rx filters at BS is performed.

B. Transmit and receive filter at BS

In this section, three different cases of transmit (Tx) and receive (Rx) filter design at BS are presented. The filters have been introduced for a scenario with $K = 2$ mobile stations in [5]. In the first case (case Diag), only the power distribution at BS is optimized. In this case, the Tx and Rx filters are given by

$$\mathbf{Q}_{\mathrm{BS},t} = \rho \mathbf{A}, \tag{20a}$$

$$\mathbf{D}_{\mathrm{BS},t} = \mathbf{I}_M \tag{20b}$$

where $\mathbf{A} = P_{\mathrm{BS}}/M \cdot \mathrm{diag}[\alpha_1, \alpha_2, ..., \alpha_K]$ with α_k a weighting parameter for the power distribution at BS, $0 \leq \alpha \leq 1$, and with ρ a scalar value to fulfill the power constraint at BS. The weighting matrix $\mathbf{A}$ is defined carrier independent.

To further increase the achievable sum rate, the Tx and Rx filters at BS have to be optimized based on the overall channels and, therewith, dependent on $\mathbf{G}_t$. The design of the BS filters is based on minimizing the MSE. Thus, in the second case (case Rx), the Rx filters at BS are optimized dependent on $\mathbf{G}_t$ to minimize the MSE on the overall channels $\mathbf{H}_{\mathrm{Rx},t}$ of (6b). In case Rx, the Tx and Rx filters at BS on subcarrier t are given by

$$\mathbf{Q}_{\mathrm{BS},t} = \rho\mathbf{A}, \tag{21a}$$

$$\mathbf{D}_{\mathrm{BS},t} = \mathbf{H}_{\mathrm{Rx},t}^{\mathrm{H}}(\mathbf{H}_{\mathrm{Rx},t}\mathbf{H}_{\mathrm{Rx},t}^{\mathrm{H}} + \mathbf{N}_t)^{-1}, \tag{21b}$$

respectively, with $\mathbf{N}_t = \sigma_n^2\mathbf{I}_M + \mathbf{H}_{\mathrm{BS},t}^{\mathrm{T}}\mathbf{G}_t\mathbf{G}_t^{\mathrm{H}}\mathbf{H}_{\mathrm{BS},t}^{*}\sigma_{\mathrm{n,RS}}$ the noise matrix. In the third case (case Rx&Tx), the Tx filters at BS are additionally optimized. The Tx filter on subcarrier t is based on the overall channel $\mathbf{H}_{\mathrm{Tx},t}$ of (6a). Thus, the filters for case Rx&Tx are given by

$$\mathbf{Q}_{\mathrm{BS},t} = \rho(\mathbf{H}_{\mathrm{Tx},t}^{\mathrm{H}}\mathbf{A}\mathbf{H}_{\mathrm{Tx},t} + K\sigma_n^2\mathbf{I}_M)^{-1}\mathbf{H}_{\mathrm{Tx},t}^{\mathrm{H}}\mathbf{A}, \tag{22a}$$

$$\mathbf{D}_{\mathrm{BS},t} = \mathbf{H}_{\mathrm{Rx},t}^{\mathrm{H}}(\mathbf{H}_{\mathrm{Rx},t}\mathbf{H}_{\mathrm{Rx},t}^{\mathrm{H}} + \mathbf{N}_t)^{-1}. \tag{22b}$$

C. Numerical optimizations

To fulfill the asymmetric rate requirements and to achieve equality for the BS to mobile station data rates, the transmit power distribution $\mathbf{A}$ at BS, the weighting parameters w_k of the WMMSE-SI relay transceive filter and the transmit powers of the mobile stations are numerically optimized. To obtain an approach with low complexity, part of the optimizations are decoupled as shown in the lower half of Figure 2. Firstly, the weights w_k of the relay transceive filter are optimized to increase C_{sum} of (13). To optimize these weights, it is assumed that the weights are the same on each subcarrier. Increasing a weight w_k from $w_k = 1$ towards $w_k = 1+\epsilon$ increases C_{BS_k} and decreases C_{S_k}, $0 < \epsilon < 1$. During the optimization of the weights w_k, the weighting parameters α_k of the Tx filter at BS are also optimized to fulfill constraint (12b). In case Rx&Tx, the Tx filter at BS is based on the overall channel $\mathbf{H}_{\mathrm{Tx},t}$ of (6a) and, is thus, dependent on the relay transceive filter $\mathbf{G}_t$. To compute $\mathbf{H}_{\mathrm{Tx},t}$, the unweighted relay transceive filter with weights $w_k = 1$, $\forall k$, is used. Secondly, the transmit powers $P_{\mathrm{S}_k,t} \leq P_{\mathrm{MS,max}}$ of the mobile stations are numerically optimized to fulfill the asymmetric rate requirements. In case of applying the hybrid one-/two-way transmission scheme, the transmit powers of S_k are zero on some subcarriers. For the optimization of the transmit powers on the remaining subcarriers, it is assumed that the transmit powers of S_k are equal on each of the remaining subcarriers. Thus, the transmit power for the remaining subcarriers is independent of the subcarrier t, if $P_{\mathrm{S}_k,t} \neq 0 \rightarrow P_{\mathrm{S}_k,t} = P_{\mathrm{S}_k}$. During the optimization of the transmit powers P_{S_k}, the weighting parameters α_k of the Tx filter at BS are also optimized as described above to fulfill constraint (12b). Thirdly, the WMMSE-SI relay transceive filter has to be recalculated and an alternating optimization between the relay transceive filter and the transmit powers of the mobile stations is performed until the constraints (12a) and (12b) are fulfilled and no further sum rate improvement is achieved. This suboptimal approach for the numerical optimization is an extension of the approach presented in [5] to the transmission via multiple subcarriers.

VI. Performance results

For obtaining numerical results, it is assumed that $P_{\mathrm{BS,max}} = P_{\mathrm{RS,max}} = 4P_{\mathrm{MS,max}}$ and $\sigma_{n,\mathrm{RS}}^2 = \sigma_{\mathrm{n}}^2$. The considered scenario consists of a base station with $M = 4$ antennas, $K = 4$ mobile stations and of a relay station with $L \geq 4$ antennas. The bidirectional communications are performed via $T = 8$ orthogonal subcarriers. The average path-losses on the i.i.d. Rayleigh fading channels from BS to RS and from the mobile stations to RS on each subcarrier are equal. The path-losses result in an average receive signal to noise ratio per data stream of 15dB at each antenna at RS if the mobile stations transmit with maximum power.

In Figure 3, the performance of the hybrid one-/two-way transmission scheme "1-/2-way" and of a pure two-way relaying scheme "2-way" as presented in [5] are compared for different asymmetric rate requirements r. The simulations are performed for $L = 8$ antennas at RS. The three different cases, i.e., case Rx&Tx, case Rx and case Diag, correspond to different Tx and Rx filters at BS as presented in Section V-B. If the filter design at BS is improved from case Diag over case Rx to case Rx&Tx, the achievable sum rate increases for the pure two-way relaying scheme as well as for the hybrid one-/two-way transmission scheme. However, for the hybrid scheme, the performance gap between case Diag and the other two cases significantly decreases for increasing r. For high asymmetric rate requirements $r > 4$, the gap between the achievable sum rates for all three cases is smaller than 2%. The performance of the hybrid one-/two-way transmission scheme is better than the performance of the pure two-way scheme for all three cases if $r > 1$. For an increasing asymmetric rate requirement r, the achievable sum rate is limited by the downlink data rate. Thus, the hybrid one-/two-way transmission scheme performs better than pure two-way relaying for higher values of r, because less data streams are simultaneously transmitted in uplink direction and "MS-MS-interference" is reduced which increases the achievable downlink data rates. For $r > 3$, the hybrid one-/two-way transmission scheme achieves even higher sum rates in case Diag than the pure two-way scheme in case Rx&Tx.

In Figure 4, the performance of the hybrid one-/two-way transmission scheme "1-/2-way" and of a pure two-way relaying scheme "2-way" as presented in [5] are compared for different numbers L of antennas at RS. The simulations are performed for an asymmetric rate requirement of $r = 3$. Similar to the previous performance

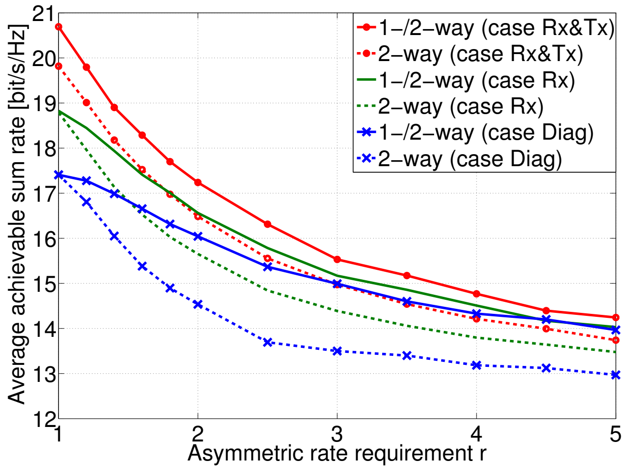

Fig. 3. Average achievable sum rates versus different asymmetric rate requirements r for $K = 4$, $T = 8$ and $L = 8$.

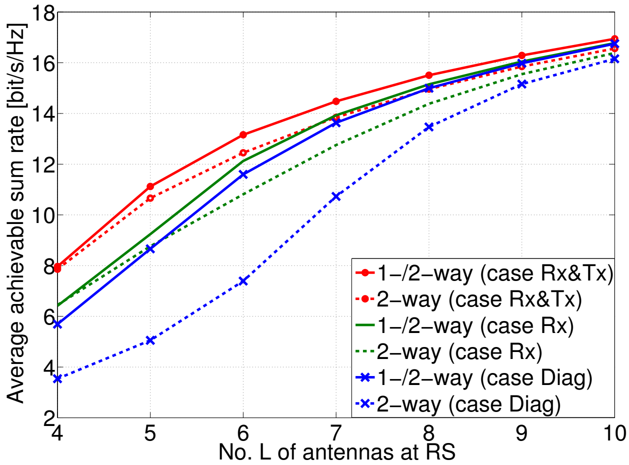

Fig. 4. Average achievable sum rates versus different numbers L of antennas at RS for $r = 3$, $T = 8$ and $K = 4$.

results, the achievable sum rate increases for the pure two-way relaying scheme as well as for the hybrid one-/two-way transmission scheme if the filter design at BS is improved from case Diag over case Rx to case Rx&Tx. Additionally, the performance of the hybrid one-/two-way transmission scheme is better than the performance of pure two-way relaying for all three cases. For $L \geq 7$ antennas at RS, the hybrid one-/two-way transmission scheme achieves similar sum rates in case Diag than the pure two-way scheme achieves in case Rx&Tx. For higher numbers $L > 8$ of antennas at RS, the performance gap between the different approaches decreases, because RS has more antennas than it requires to spatially separate all received signals.

VII. Conclusions

Non-regenerative two-hop relaying for a multi-user multi-carrier scenario consisting of a multi-antenna base station and several single antenna mobile stations has been investigated. To maximize the achievable sum rate under asymmetric rate requirements, a hybrid one-/two-way transmission scheme per subcarrier has been proposed. Furthermore, different cases of transmit and receive filter designs at the base station have been investigated. In all cases, the proposed hybrid one-/two-way transmission scheme achieved higher sum rates than a pure two-way relaying scheme in case of asymmetric rate requirements of $r > 1$.

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