A Hybrid Approach Combining Non-Regenerative MIMO Two-Way Relaying and Direct Link Transmission

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***Abstract*—In this paper, two different transmission schemes which are based on the joint consideration of two-way relaying and direct link transmission are proposed. The considered scenario consists of two half-duplex multi-antenna nodes which want to bidirectionally exchange information under asymmetric data rate requirements. To enable the communications, the nodes can either perform transmissions via the direct link or via an intermediate non-regenerative multi-antenna half-duplex relay station, termed RS. To maximize the achievable data rates under asymmetric data rate requirements, a hybrid approach is proposed which combines the transmissions via two-way relaying and via the direct link using two orthogonal time resources. Furthermore, an approach is introduced which performs the transmissions either via two-way relaying or via the direct link depending on the instantaneous channel conditions. Additionally, a joint filter design approach for the spatial filters at the nodes and at RS is presented considering the same number of antennas at both nodes and at RS. The performances of the proposed transmission schemes are investigated by numerical results and it is shown that both schemes achieve higher data rates than conventional approaches which consider pure two-way relaying or pure direct link transmissions.**

I. Introduction

In many wireless applications, two nodes want to bidirectionally exchange information. Transmissions via the direct link, termed direct transmissions, between the nodes have been extensively studied in [1] and references therein. For these direct transmissions, the achievable data rates typically decrease with increasing distances and shadowing effects. Considering a three node network enables the consideration of two-hop transmissions [2]. Instead of a pure direct transmission (DT), the data exchange can be performed via an intermediate relay station which can overcome shadowing effects, expand the communication range and increase the achievable throughput [3]–[6]. In [3], [4], the optimization of the filter design at a multi-antenna source node and at multi-antenna relay station, termed RS, is investigated for one-way relaying. In [5], [6], the direct link between the source and the destination node is additionally considered and optimal filter designs are presented.

Assuming half-duplex nodes and a half-duplex relay station and considering time-division duplex, two time slots are required to perform a unidirectional transmission from a source node to a destination node with the one-way relaying scheme. To enable a bidirectional communication between two nodes, four time slots are required, because each node requires separate orthogonal resources for the transmission and reception to and from RS, respectively. Thus, more resources are required compared to performing a DT between the nodes.

To overcome this drawback, the two-way relaying (TWR) scheme introduced in [7] can be applied which only requires two time slots to support the bidirectional communication via an intermediate relay station. In non-regenerative two-way relaying, both nodes transmit simultaneously to RS in the first time slot. In the second time slot, RS linearly processes and retransmits the received signals of both nodes and after subtracting the back-propagated self-interference at each node, the desired signal can be recovered [7].

Non-regenerative multi-antenna TWR in a single-pair scenario is investigated, e.g., in [8]–[12]. In [8], multi-antenna TWR is extensively studied and different relay transceive filter designs are investigated. In [9], a gradient based transceive filter approach for sum rate maximization is presented and in [10], joint source and relay precoding designs are investigated. A relay transceive strategy maximizing the weighted sum of the Frobenius norms of the effective single-user channels is introduced in [11].

If TWR is applied, transmissions via the direct link can no longer be considered due to the half-duplex constraint of the nodes. Thus, a 3-phase two-way protocol is considered in [13] which enables direct link transmissions. However, the achievable sum rate of the 3-phase TWR protocol is worse than the achievable sum rate of conventional TWR for weak direct links and is worse than the achievable sum rate of pure DT for strong direct links.

In this paper, the considered scenario consist of two half-duplex multi-antenna nodes which want to bidirectionally exchange information. The nodes are capable of performing transmissions via the direct link as well as TWR transmissions via an intermediate non-regenerative half-duplex multi-antenna relay station. In TWR [8]–[12], the considered number of antennas at RS is typically larger than the considered number of antennas at each node. However, we want to focus on a scenario where a mobile node is acting as a relay. Thus, we assume that the number of antennas at RS is equal to the number of antennas at each node.

If two nodes bidirectionally exchange information, the required data rates for each direction of transmission may be different which can be considered by introducing asymmetric data rate (ADR) requirements [12]. We assume that the data rate which is required for the transmission from one node S_1 to another node S_2 shall be r times the data rate which is required for the transmission from S_2 to S_1, $1 \leq r \leq \infty$. Considering pure DT and assuming channel reciprocity, the achievable sum rate is independent of r because the time sharing between the transmission from S_1 to S_2 and the transmission from S_2 to S_1 can be optimized to fulfill the ADR requirement. For pure TWR, the achievable sum rate decreases for increasing r because TWR is intentionally designed to support symmetric data rates. However, if pure TWR achieves higher data rates than pure DT for $r = 1$ and pure DT achieves higher data rates than pure TWR for $r \rightarrow \infty$, TWR and DT can be combined to increase the achievable sum rate for $1 \leq r \leq \infty$.

In this paper, we propose a hybrid TWR/DT transmission scheme which combines the transmissions via TWR and via the direct link using two orthogonal time resources to maximize the achievable sum rate under the considered ADR requirements. Furthermore, we propose a selection TWR/DT approach which performs the bidirectional transmissions either via TWR or via the direct link depending on which scheme achieves a higher sum rate for the instantaneous channel conditions under the considered ADR requirements. Additionally, we present a joint filter design of the spatial filters at the nodes and at RS assuming an equal number of antennas at the nodes and at RS.

The rest of the paper is organized as follows. In Section II, the system model for TWR and DT is presented, the considered transmission schemes are introduced and ADR requirements are discussed. In Section III, the multiple-input multiple-output (MIMO) filter design at the nodes and at RS is described. The different optimization problems which arise by considering ADR requirements for the proposed transmission schemes are presented in Section IV. Numerical results in Section V confirm the analytical investigations and Section VI concludes the paper.

Notations: The operator $\mathrm{E}[\cdot]$ denotes the expectation of the random variables within the brackets. The operator $||\cdot||_\mathrm{F}$ denotes the Frobenius norm of a complex matrix and $\mathbf{I}_M$ denotes an identity matrix of size M.

II. System Model and Transmission Schemes

As shown in Figure 1, a scenario consisting of two half-duplex multi-antenna nodes S_1 and S_2 and of an intermediate half-duplex non-regenerative multi-antenna relay station RS, all equipped with the same number M of antennas, is considered. The nodes S_1 and S_2 want to bidirectionally exchange information and the transmit power at each node and at RS is limited by P_Node and P_RS, respectively. Channel reciprocity is assumed and the channels $\mathbf{H}_1 \in \mathbb{C}^{M\times M}$ and $\mathbf{H}_2 \in \mathbb{C}^{M\times M}$ from S_1 and S_2 to RS, respectively, as well as the direct link channel $\mathbf{H}_\mathrm{DL} \in \mathbb{C}^{M\times M}$ are assumed to be constant during

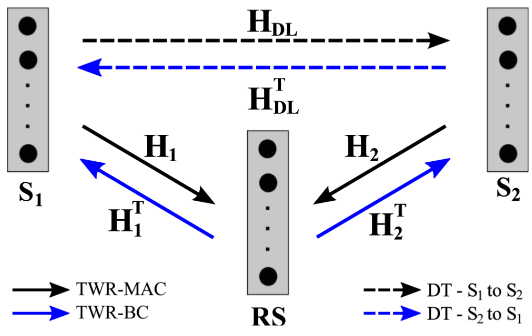

Fig. 1. System model

one cycle of the considered transmission schemes which are introduced in Section II-C.

All transmitted signals are assumed to be statistically independent and the noises at RS and at the nodes are assumed to be independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) with zero mean and variances $\sigma^2_\mathrm{n,RS}$ and σ^2_n, respectively. Due to the half-duplex constraint, the nodes S_1 and S_2 can either perform TWR via RS or the nodes can successively transmit via the direct link channel to bidirectionally exchange information. In the following, the system equations for TWR are presented. Afterwards, the system equations for considering transmissions via the direct link channel are presented. Finally, the transmission schemes are introduced and the consideration of ADR requirements is discussed.

A. Two-way relaying

In TWR, both nodes are simultaneously transmitting to RS in the first phase [7]. This phase is termed TWR multiple access phase (TWR-MAC) as shown in Figure 1. The transmitted symbols of S_k, $k = 1, 2$, are contained in the vector $\mathbf{s}_k \in \mathbb{C}^{M\times 1}$ with $\mathrm{E}[\mathbf{s}_k\mathbf{s}_k^\mathrm{H}] = \mathbf{I}_M$. Using the transmit filter matrix $\mathbf{Q}_k \in \mathbb{C}^{M\times M}$ with $||\mathbf{Q}_k||^2_\mathrm{F} \leq P_\mathrm{Node}$ at S_k, the received baseband signal at RS is given by

$$\mathbf{y}_\mathrm{RS} = \mathbf{H}_1\mathbf{Q}_1\mathbf{s}_1 + \mathbf{H}_2\mathbf{Q}_2\mathbf{s}_2 + \mathbf{n}_\mathrm{RS}, \tag{1}$$

where $\mathbf{n}_\mathrm{RS} \in \mathbb{C}^{M\times 1}$ represents the complex white Gaussian noise vector at RS. RS linearly processes the received signal using the relay transceive filter matrix $\mathbf{G} \in \mathbb{C}^{M\times M}$ and retransmits the linearly processed version of $\mathbf{y}_\mathrm{RS}$ back to the nodes in the second phase. This phase is termed TWR broadcast (TWR-BC) as shown in Figure 1. To fulfill the power constraint at RS during the retransmission, the relay transceive filter can be written as [12]

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

where $\widetilde{\mathbf{G}} \in \mathbb{C}^{M\times M}$ is a relay transceive filter which does not implicitly fulfill the power constraint and γ is a scalar value to satisfy the relay power constraint. It is given by

$$\gamma = \sqrt{\frac{P_\mathrm{RS}}{\sum_{k=1}^{2}||\widetilde{\mathbf{G}}\mathbf{H}_k\mathbf{Q}_k||^2_F + ||\widetilde{\mathbf{G}}||^2_\mathrm{F}\sigma^2_\mathrm{n,RS}}}. \tag{3}$$

In the TWR-BC phase, the received signal at S_k is given by [12]

$$\mathbf{y}_{\mathrm{S}_k,\mathrm{interf.}} = \mathbf{H}_k^{\mathrm{T}}\mathbf{G}(\mathbf{H}_k\mathbf{Q}_k\mathbf{s}_k + \mathbf{H}_i\mathbf{Q}_i\mathbf{s}_i + \mathbf{n}_{\mathrm{RS}}) + \mathbf{n}_{\mathrm{S}k},$$
$$i = 1,2, i \neq k, \quad (4)$$

where $\mathbf{n}_{\mathrm{S}k} \in \mathbb{C}^{M\times 1}$ represents the complex white Gaussian noise vector at S_k. Is it assumed that $\mathbf{H}_k^{\mathrm{T}}\mathbf{G}\mathbf{H}_k$ is perfectly known at S_k. Thus, the back-propagated self-interference can be canceled [7] and the received signal at S_k reduces to

$$\mathbf{y}_{\mathrm{S}_k} = \mathbf{H}_k^{\mathrm{T}}\mathbf{G}(\mathbf{H}_i\mathbf{Q}_i\mathbf{s}_i + \mathbf{n}_{\mathrm{RS}}) + \mathbf{n}_{\mathrm{S}k}. \quad (5)$$

Let us define the matrices

$$\mathbf{A}_{i\to k} = \mathbf{H}_k^{\mathrm{T}}\mathbf{G}\mathbf{H}_i\mathbf{Q}_i, \quad (6)$$
$$\mathbf{B}_k = \sigma_{\mathrm{n,RS}}^2\mathbf{H}_k^{\mathrm{T}}\mathbf{G}\mathbf{G}^{\mathrm{H}}\mathbf{H}_k^* + \sigma_n^2\mathbf{I}_M, \quad (7)$$

describing the overall channel from Si to Sk and the noise autocorrelation matrix at Sk, respectively. Using these matrices, the achievable data rate from Si to Sk in TWR is given by

$$C_{\mathrm{TWR}}^{\mathrm{S}_i\to\mathrm{S}_k} = \frac{1}{2}\log_2(\det(\mathbf{I}_M + \mathbf{A}_{i\to k}\mathbf{A}_{i\to k}^{\mathrm{H}}\mathbf{B}_k^{-1})),$$
$$i,k = 1,2, i\neq k, \quad (8)$$

where the factor $1/2$ is needed because two time slots of equal duration are used to perform the overall transmission.

B. Transmissions via the Direct Link (DT)

Considering DT, the nodes cannot transmit simultaneously due to the half-duplex constraint. Thus, in the first phase, S_1 transmits to S_2 and in the second phase, S_2 transmits to S_1 as shown in Figure 1. The durations of both phases can be different and the optimization of the durations of both phases is investigated in Section IV. The achievable data rates from S_1 to S_2 and vice versa considering DT are given by

$$C_{\mathrm{DT}}^{\mathrm{S}_1\to\mathrm{S}_2} = \log_2(\det(\mathbf{I}_M + \frac{1}{\sigma_{\mathrm{n}}^2}\mathbf{H}_{\mathrm{DL}}\mathbf{Q}_1\mathbf{Q}_1^{\mathrm{H}}\mathbf{H}_{\mathrm{DL}}^{\mathrm{H}})), \quad (9)$$
$$C_{\mathrm{DT}}^{\mathrm{S}_2\to\mathrm{S}_1} = \log_2(\det(\mathbf{I}_M + \frac{1}{\sigma_{\mathrm{n}}^2}\mathbf{H}_{\mathrm{DL}}^{\mathrm{T}}\mathbf{Q}_2\mathbf{Q}_2^{\mathrm{H}}\mathbf{H}_{\mathrm{DL}}^*)), \quad (10)$$

respectively.

C. Transmission Schemes

In this paper, four different transmission schemes are considered which are described in this section. The schemes are termed pure TWR, pure DT, selection TWR/DT and hybrid TWR/DT.

Applying the pure TWR scheme, all transmissions are performed via TWR as described in Section II-A. In this case, the direct link is not considered.

Applying the pure DT scheme, all transmissions are performed via the direct link as described in Section II-B. In this case, transmissions via the intermediate relay station are not considered.

To consider transmissions via the direct link and via TWR, two additional transmission schemes are proposed. The selection TWR/DT scheme either performs the transmissions via TWR or via the direct link dependent on the instantaneous channel conditions. If transmissions via TWR achieve higher data rates than transmissions via the direct link, the selection TWR/DT scheme performs TWR, and if transmissions via the direct link achieve higher data rates than transmissions via TWR, DTs are performed. The selection TWR/DT scheme selects for each channel realization the approach which achieves the highest data rate.

The hybrid TWR/DT scheme combines the transmissions via the direct link and via TWR using orthogonal time resources. In the first phase, TWR is performed. In the second phase, a transmission via the direct link is performed only in one link direction, i.e., either S_1 transmits data to S_2 or S_2 transmits data to S_1. The duration of the TWR phase is given by $T_{\mathrm{TWR}} = \alpha T$ and the duration of the DT phase is given by $T_{\mathrm{DT}} = (1-\alpha)T$, where T is the overall duration of both phases and where α, $0 \leq \alpha \leq 1$, is a parameter to adjust the duration of performing TWR with respect to the duration of performing DT.

To describe the achievable data rates of all schemes in a general equation, the parameter β, $0 \leq \beta \leq 1$, is introduced to adjust the duration of performing a transmission via the direct link from S_1 to S_2 with respect to the duration of performing a transmission via the direct link from S_2 to S_1. The parameters α and β for the considered transmission schemes are given by:

- pure TWR: $\alpha = 1$ (the value of β has no impact),
- pure DT: $\alpha = 0$ and $0 \leq \beta \leq 1$,
- selection TWR/DT: $\alpha = 1$ or $\alpha = 0$ and $0 \leq \beta \leq 1$,
- hybrid TWR/DT: $0 \leq \alpha \leq 1$ and $\beta = 0$ or $\beta = 1$.

Thus, the achievable data rates can be written as

$$C_{\mathrm{sum}}^{\mathrm{S}_1\to\mathrm{S}_2} = \alpha C_{\mathrm{TWR}}^{\mathrm{S}_1\to\mathrm{S}_2} + \beta(1-\alpha)C_{\mathrm{DT}}^{\mathrm{S}_1\to\mathrm{S}_2}, \quad (11)$$
$$C_{\mathrm{sum}}^{\mathrm{S}_2\to\mathrm{S}_1} = \alpha C_{\mathrm{TWR}}^{\mathrm{S}_2\to\mathrm{S}_1} + (1-\beta)(1-\alpha)C_{\mathrm{DT}}^{\mathrm{S}_1\to\mathrm{S}_2}, \quad (12)$$

and the overall sum rate is given by

$$C_{\mathrm{sum}} = C_{\mathrm{sum}}^{\mathrm{S}_1\to\mathrm{S}_2} + C_{\mathrm{sum}}^{\mathrm{S}_2\to\mathrm{S}_1}. \quad (13)$$

D. Asymmetric Data Rate Requirements

In this paper, we assume that the data rate which is required for the transmission from S_1 to S_2 shall be r times the data rate which is required for the transmission from S_2 to S_1 and without loss of generality we assume $r \geq 1$ because S_1 and S_2 can be interchanged. Thus, we require that the achievable data rate $C_{\mathrm{sum}}^{\mathrm{S}_1\to\mathrm{S}_2}$ (11) for the transmission from S_1 to S_2 has to be r times the achievable data rate $C_{\mathrm{sum}}^{\mathrm{S}_2\to\mathrm{S}_1}$ (12) for the transmission from S_2 to S_1, leading to the following optimization constraint:

$$C_{\mathrm{sum}}^{\mathrm{S}_1\to\mathrm{S}_2} = rC_{\mathrm{sum}}^{\mathrm{S}_2\to\mathrm{S}_1}. \quad (14)$$

In Section IV, the optimization problems to maximize the achievable sum rate under this constraint are described for the considered transmission schemes.

III. MIMO Filter Design

In this section, the transmit (Tx) and receive (Rx) filter design at the nodes as well as the filter design at RS is presented. First, the filter design for performing DT between the nodes is presented. Secondly, the filter design for TWR is described.

A. Filter Design for DT

If DT is performed, MIMO Tx and Rx filters based on the eigendirections of the channel as presented in [1] are applied at the nodes. Let the singular value decomposition (SVD) of the channel $\mathbf{H}_{\mathrm{DL}}$ from S_1 to S_2 be given by $\mathbf{H}_{\mathrm{DL}} = \mathbf{U}_{\mathrm{DL}}\mathbf{\Lambda}_{\mathrm{DL}}^{1/2}\mathbf{V}_{\mathrm{DL}}^{\mathrm{H}}$, where $\mathbf{U}_{\mathrm{DL}}$ contains the left singular vectors, $\mathbf{V}_{\mathrm{DL}}$ contains the right singular vectors and $\mathbf{\Lambda}_{\mathrm{DL}}$ contains the corresponding eigenvalues of the channel $\mathbf{H}_{\mathrm{DL}}$ in decreasing order. For the transmission from S_1 to S_2, the Tx filter at S_1 is given by

$$\mathbf{Q}_1 = \mathbf{V}_{\mathrm{DL}}\mathbf{W}_{\mathrm{DT},1}, \tag{15}$$

where $\mathbf{W}_{\mathrm{DT},1}$ is a diagonal matrix describing the waterfilling power allocations [1]. The Rx filter at S_2 is given by

$$\mathbf{D}_2 = \mathbf{U}_{\mathrm{DL}}^{\mathrm{H}}. \tag{16}$$

For the transmission from S_2 to S_1, the Tx filter at S_2 is given by

$$\mathbf{Q}_2 = \mathbf{U}_{\mathrm{DL}}^{*}\mathbf{W}_{\mathrm{DT},2}, \tag{17}$$

where $\mathbf{W}_{\mathrm{DT},2}$ is again a diagonal matrix describing the waterfilling power allocations [1]. The Rx filter at S_1 is given by

$$\mathbf{D}_1 = \mathbf{V}_{\mathrm{DL}}^{\mathrm{T}}. \tag{18}$$

B. Filter Design for TWR

For TWR, the Tx and Rx filters at the nodes are designed together with the relay transceive filter in a two-step approach to handle the $2M$ data streams which are simultaneously received at RS in TWR-MAC and which have to be simultaneously retransmitted in TWR-BC. First, the design of the relay transceive filter $\mathbf{G}$ is considered and we propose an efficient suboptimal approach. Due to the limited number M of antennas at RS, the $2M$ data streams which are simultaneously received at RS in TWR-MAC cannot be spatially separated. We propose to utilize the relay transceive filter design for one-way relaying which is presented in [5] adjusted for the transmission from S_1 to S_2 to support higher data rates in this direction. Let the SVD of the channel from S_k to RS be given by $\mathbf{H}_k = \mathbf{U}_k\mathbf{\Lambda}_k^{1/2}\mathbf{V}_k^{\mathrm{H}}$, where $\mathbf{U}_k$ contains the left singular vectors, $\mathbf{V}_k$ contains the right singular vectors and $\mathbf{\Lambda}_k$ contains the corresponding eigenvalues of the channel $\mathbf{H}_k$ in decreasing order. To support higher data rates transmitted from S_1 to S_2 than vice versa, the relay transceive filter of (2) is given by

$$\mathbf{G} = \gamma\widetilde{\mathbf{G}} = \gamma\mathbf{V}_2\mathbf{W}_{\mathrm{TWR}}\mathbf{U}_1^{\mathrm{H}}, \tag{19}$$

where $\mathbf{W}_{\mathrm{TWR}}$ is a diagonal matrix to optimize the power allocation at RS. The mth component in the diagonal weighting matrix $\mathbf{W}_{\mathrm{TWR}}$ is

$$w_m = \sqrt{\frac{\left[\sqrt{\mu\kappa\frac{\lambda_{k,m}}{\lambda_{i,m}} + \left(\kappa\frac{\lambda_{k,m}}{2\lambda_{i,m}}\right)^2} - \kappa\frac{\lambda_{k,m}}{2\lambda_{i,m}} - \frac{\sigma_n^2}{\lambda_{i,m}}\right]^+}{(P_{\mathrm{Node}}/M)\lambda_{k,m} + \sigma_{n,RS}^2}},$$
$$\kappa = \frac{P_{\mathrm{Node}}\sigma_n^2}{M\sigma_{n,RS}^2},$$
$$m = 1, 2, ..., M, \tag{20}$$

where μ is a constant to fulfill the power constraint at RS for $\gamma = 1$ and $\lambda_{k,m}$ is the mth element on the diagonal of $\mathbf{\Lambda}_k$.

Secondly, the Tx and Rx filters at the nodes have to be designed. To determine these filters, we apply a MIMO filter design based on transmitting and receiving in the eigendirections of the overall channels $\mathbf{H}_{\mathrm{ov},1} = \mathbf{H}_2^{\mathrm{T}}\mathbf{G}\mathbf{H}_1$ and $\mathbf{H}_{\mathrm{ov},2} = \mathbf{H}_1^{\mathrm{T}}\mathbf{G}\mathbf{H}_2$. Let the SVD of $\mathbf{H}_{\mathrm{ov},1}$ and $\mathbf{H}_{\mathrm{ov},2}$ be given by $\mathbf{H}_{\mathrm{ov},1} = \mathbf{U}_{\mathrm{ov},1}\mathbf{\Lambda}_{\mathrm{ov},1}^{1/2}\mathbf{V}_{\mathrm{ov},1}^{\mathrm{H}}$ and $\mathbf{H}_{\mathrm{ov},2} = \mathbf{U}_{\mathrm{ov},2}\mathbf{\Lambda}_{\mathrm{ov},2}^{1/2}\mathbf{V}_{\mathrm{ov},2}^{\mathrm{H}}$, respectively. Thus, the Tx filters at the nodes S_1 and S_2 are given by

$$\mathbf{Q}_1 = \sqrt{\frac{P_1}{M}}\mathbf{V}_{\mathrm{ov},1}\mathbf{W}_1, \tag{21}$$

$$\mathbf{Q}_2 = \sqrt{\frac{P_2}{M}}\mathbf{V}_{\mathrm{ov},2}, \tag{22}$$

respectively, where $\mathbf{W}_1$ is a diagonal waterfilling matrix for the overall channel $\mathbf{H}_{\mathrm{ov},1}$ with unit norm and where $P_1 \leq P_{\mathrm{node}}$ and $P_2 \leq P_{\mathrm{node}}$ are the transmit powers at the nodes which are optimized according to the algorithms described in Section IV. The Rx filters at the nodes are given by

$$\mathbf{D}_1 = \mathbf{U}_{\mathrm{ov},2}^{\mathrm{H}}, \tag{23}$$

$$\mathbf{D}_2 = \mathbf{U}_{\mathrm{ov},1}^{\mathrm{H}}. \tag{24}$$

IV. Optimization Problems for the Considered Transmission Schemes under ADR Requirements

In this section, the optimization problems to maximize the achievable sum rate under the constraint (14) are described for the four considered transmission schemes.

A. Pure TWR

In pure TWR, the optimization problem is given by

$$\max_{P_1, P_2} C_{\mathrm{sum}}, \tag{25a}$$

$$\text{subject to: } P_i \leq P_{\mathrm{Node}},\ i = 1, 2, \tag{25b}$$

$$C_{\mathrm{sum}}^{\mathrm{S}_1\rightarrow\mathrm{S}_2} = rC_{\mathrm{sum}}^{\mathrm{S}_2\rightarrow\mathrm{S}_1}. \tag{25c}$$

The constraints can be fulfilled by optimizing the transmit powers P_1 and P_2 at S_1 and S_2, respectively. First, the achievable data rates $C_{\mathrm{TWR}}^{\mathrm{S}_1\rightarrow\mathrm{S}_2}$ and $C_{\mathrm{TWR}}^{\mathrm{S}_2\rightarrow\mathrm{S}_1}$ are computed according to (8). Secondly, if $C_{\mathrm{TWR}}^{\mathrm{S}_1\rightarrow\mathrm{S}_2} < rC_{\mathrm{TWR}}^{\mathrm{S}_2\rightarrow\mathrm{S}_1}$, the transmit power P_2 is reduced until (25c) is fulfilled. Otherwise, if $C_{\mathrm{TWR}}^{\mathrm{S}_1\rightarrow\mathrm{S}_2} > rC_{\mathrm{TWR}}^{\mathrm{S}_2\rightarrow\mathrm{S}_1}$ the transmit power P_1 is reduced until (25c) is fulfilled. To obtain the optimal transmit power

$0 < P_1 \leq P_{\text{Node}}$ or $0 < P_2 \leq P_{\text{Node}}$ which fulfills the constraint (25c), the bisection method can be applied.

B. Pure DT

In case of pure DT, the optimization problem is given by

$$\max_{\beta} C_{\text{sum}}, \tag{26a}$$

$$\text{subject to: } C_{\text{sum}}^{\text{S}_1\rightarrow\text{S}_2} = rC_{\text{sum}}^{\text{S}_2\rightarrow\text{S}_1}. \tag{26b}$$

The time duration $0 \leq \beta \leq 1$ of the transmission from S_1 to S_2 is optimized with respect to the time duration $1-\beta$ of the transmission from S_2 to S_1 and both transmissions are performed with maximum transmit power at the nodes. Due to the assumption of channel reciprocity, $C_{\text{DT}}^{\text{S}_1\rightarrow\text{S}_2} = C_{\text{DT}}^{\text{S}_2\rightarrow\text{S}_1}$. Thus, the time duration of the transmission from S_1 to S_2 is r times the time duration of the transmission from S_2 to S_1.

C. Selection TWR/DT

Depending on the instantaneous channel gains between the nodes and RS in comparison to the instantaneous channel gain of the direct link, either pure TWR outperforms pure DT or vice versa. Thus, we propose to select either pure TWR or pure DT to maximize the average achievable sum rate. First, the achievable sum rates utilizing pure TWR and pure DT are computed as described in Section IV-A and IV-B, respectively. Secondly, for each channel realization, the scheme which achieves the highest sum rate is selected to perform the transmissions.

D. Hybrid TWR/DT

The achievable sum rate of pure TWR decreases for increasing r. However, if pure TWR achieves higher data rates than pure DT for $r = 1$ and pure DT achieves higher data rates than pure TWR for $r \rightarrow \infty$, TWR and DT can be combined to increase the achievable sum rate for $1 \leq r \leq \infty$. This is exploited by the proposed hybrid TWR/DT scheme and the optimization problem is given by

$$\max_{P_1,P_2,\alpha,\beta} C_{\text{sum}}, \tag{27a}$$

$$\text{subject to: } P_i \leq P_{\text{Node}},\ i = 1,2, \tag{27b}$$

$$C_{\text{sum}}^{\text{S}_1\rightarrow\text{S}_2} = rC_{\text{sum}}^{\text{S}_2\rightarrow\text{S}_1}, \tag{27c}$$

with α and β of (11) and (12). The choice of β is jointly optimized with α and with the transmit powers P_1 and P_2 of both nodes to maximize the achievable sum rate under the ADR requirement given by the constraint (27c).

V. Performance Results

In this section, numerical results on the achievable sum rates for the considered transmission schemes are investigated. For the simulations, i.i.d. Rayleigh fading channels are considered with an average path loss p_k between S_k and RS and an average path loss p_{DL} between S_1 and S_2. The average signal to noise ratio (SNR) for the transmission from S_k to RS is defined as

$$\text{SNR}_k = \frac{p_k P_{\text{Node}}}{\sigma_{n,\text{RS}}^2}, \tag{28}$$

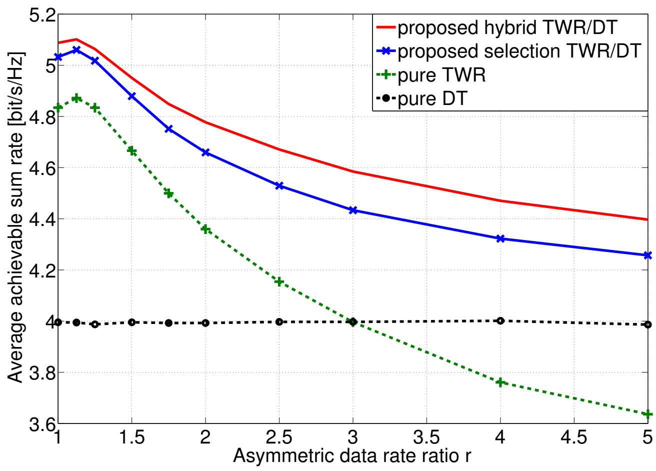

Fig. 2. Average achievable sum rates versus ADR ratio r, $M = 2$, $\text{SNR}_1 = \text{SNR}_2 = 15$dB, $\text{SNR}_{\text{DL}} = 6$dB.

and the average SNR for the transmission from S_1 to S_2 is defined as

$$\text{SNR}_{\text{DL}} = \frac{p_{\text{DL}} P_{\text{Node}}}{\sigma_n^2}. \tag{29}$$

Furthermore, it is assumed that $P_{\text{Node}} = P_{\text{RS}}$ and $\sigma_{\text{RS}}^2 = \sigma_{\text{n}}^2$.

The average achievable sum rates versus the ADR ratio $r = C^{\text{S}_1}/C^{\text{S}_2}$ are shown in Figure 2 for $\text{SNR}_1 = \text{SNR}_2 = 15$dB, $\text{SNR}_{\text{DL}} = 6$dB and $M = 2$ antennas at each node and at RS. For pure DT, the constraint (14) is fulfilled by optimizing β. Thus, the average achievable sum rates are independent of the ADR ratio because channel reciprocity is assumed and the same data rates can be achieved for each direction of transmission. The performance of pure TWR decreases for increasing r because the sum rate is limited by $C_{\text{TWR}}^{\text{S}_1\rightarrow\text{S}_2}$. To fulfill the constraint (14) while increasing r, the transmit power P_2 at node S_2 has to be decreased on average. The proposed selection TWR/DT scheme and the proposed hybrid TWR/DT scheme outperform pure TWR and pure DT. For $r = 3$, the hybrid TWR/DT scheme achieves a gain of approximately 15% compared to pure DT and pure TWR. The gain of the hybrid TWR/DT scheme compared to the selection TWR/DT scheme increases if the gap between the achievable sum rates of pure TWR and pure DT decreases. If the gap between the achievable sum rates of pure TWR and pure DT is large, the gain by combining both schemes is very small. In these cases, hybrid TWR/DT and selection TWR/DT have similar performances.

Figure 3 shows the average achievable sum rates over different SNRs of $\mathbf{H}_{\text{DL}}$ (SNR_{DL}) for $r = 3$. The proposed selection TWR/DT scheme and the proposed hybrid TWR/DT scheme achieve significantly higher sum rates than pure TWR for $\text{SNR}_{\text{DL}} > 5$dB and significantly higher sum rates than pure DT for $\text{SNR}_{\text{DL}} < 5$dB. For 4dB$\leq \text{SNR}_{\text{DL}} \leq$ 8dB, the proposed schemes achieve significantly higher sum rates than pure TWR and pure DT.

The average achievable sum rates for an asymmetry between SNR_1 and SNR_2 are shown in Figure 4 and Figure 5 for $r = 2$

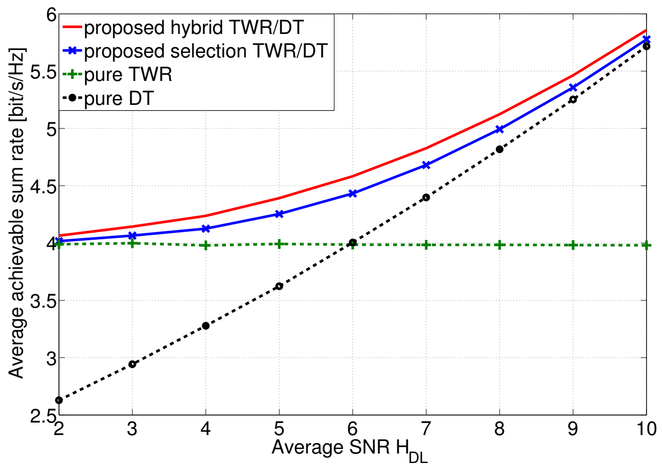

Fig. 3. Average achievable sum rates versus average $\mathrm{SNR}_{\mathrm{DL}}$ of $\mathbf{H}_{\mathrm{DL}}$, $r = 3$, $M = 2$, $\mathrm{SNR}_1 = \mathrm{SNR}_2 = 15$dB.

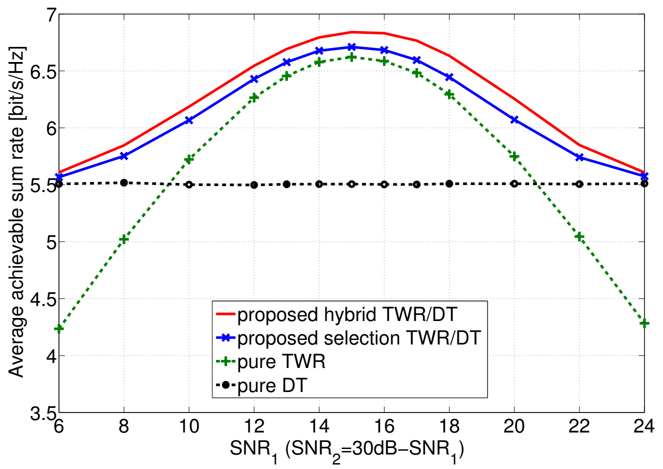

Fig. 4. Average sum rates for asymmetric SNRs ($\mathrm{SNR}_1 + \mathrm{SNR}_2 = 30$dB $r = 2$, $M = 3$)

and $r = 4$, respectively, using the values $\mathrm{SNR}_{\mathrm{DL}} = 5$dB, $M = 3$, $\mathrm{SNR}_1 + \mathrm{SNR}_2 = 30$dB. The average achievable sum rate of pure TWR decreases when increasing the asymmetry between the SNRs. Similar to the previous results, the combination of DT and TWR achieves the highest gain if the gap between the achievable sum rate of pure TWR and pure DT is small. In Figure 4, the gain is significant for $8 \leq \mathrm{SNR}_1 \leq 10$ and $20 \leq \mathrm{SNR}_1 \leq 22$. In Figure 5, the average achievable sum rates of pure TWR are smaller compared to Figure 4 because a higher ADR ratio r is assumed. Thus, the sum rates of pure TWR and pure DT are closer to each other for nearly symmetric SNRs and the gain of the proposed hybrid TWR/DT scheme is significant for $10 \leq \mathrm{SNR}_1 \leq 20$.

VI. Conclusions

Bidirectional communications under asymmetric data rate requirements of two multi-antenna nodes have been considered. The transmissions have been performed via the direct link as well as via an intermediate non-regenerative multi-

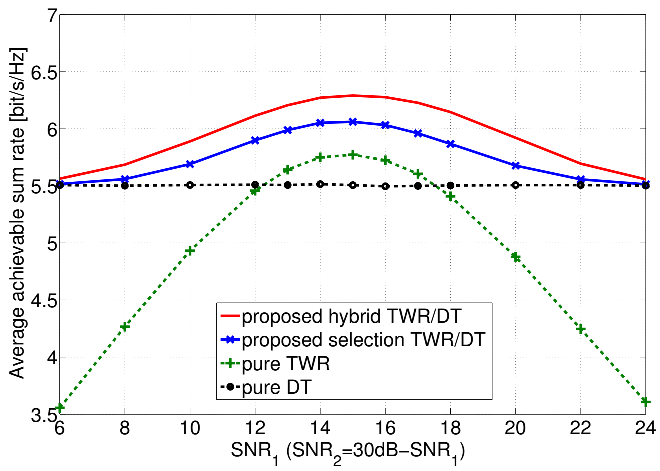

Fig. 5. Average sum rates for asymmetric SNRs ($\mathrm{SNR}_1 + \mathrm{SNR}_2 = 30$dB $r = 4$, $M = 3$)

antenna relay station. To increase the achievable sum rate, two different transmission schemes have been proposed. The selection TWR/DT scheme performs transmissions either via the direct link or via RS and the hybrid TWR/DT scheme combines a two-way relaying and a direct link transmission. Performance results show that both schemes achieve higher sum rates than schemes which are based on pure two-way relaying or pure direct link transmissions.

Acknowledgment

The work of Holger Degenhardt is funded by the Deutsche Forschungsgemeinschaft (DFG) under Grant No. Kl907/2-2 and is supported by the LOEWE Priority Program Cocoon and by the Graduate School of Computational Engineering at Technische Universität Darmstadt.

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