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Self-interference aware MIMO filter design for non-regenerative multi-pair two-way relaying

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***Abstract*—A multi-pair two-way relaying scenario with multi-antenna mobile stations is considered. The bidirectional communications between the mobile stations are supported by an intermediate non-regenerative multi-antenna relay station. It is assumed that the mobile stations can subtract the back-propagated self-interference. Different relay transceive filter design approaches which utilize the fact that the mobile stations can perform self-interference cancellation are introduced. First, a self-interference aware MMSE transceive filter is derived. Second, a multi-antenna MMSE extension of the zero-forcing block-diagonalization based approaches is proposed and an upper bound for these approaches is given. The proposed transceive filters require less antennas at the relay station and achieve higher sum rates compared to conventional relay transceive filter approaches which do not exploit the capability of the mobile stations to perform self-interference cancellation.**

I. Introduction

Relaying techniques can be used to expand the coverage of wireless networks and to increase the achievable throughput. To support multiple bidirectional communications via an intermediate half-duplex relay station RS, multi-antenna techniques can be used to spatially separate the communication pairs and to enable the simultaneous communication of all pairs. Within each pair, the two-way relaying protocol of [1] can be applied to overcome the duplexing loss of conventional one-way relaying schemes. The achievable sum rates for two-way relaying depend on the overall channel and therewith on the transceive filter design at RS. Furthermore, the achievable sum rates depend on the capability of the mobile stations to perform self-interference cancellation and on the available channel state information (CSI). If the mobile stations can subtract the back-propagated self-interference before recovering the desired signal, the achievable sum rates can be increased.

In [2] and [3], the optimal transceive filter at RS is derived for one-way relaying with multiple antennas in a single-pair scenario. Non-regenerative multi-antenna two-way relaying in a single-pair scenario is investigated in [4], [5], [6]. A minimum mean square error (MMSE) transceive filter at RS exploiting self-interference cancellation is derived in [4]. In [5], a gradient based transceive filter approach for sum rate maximization is presented and in [6] joint source and relay precoding designs are investigated. Non-regenerative multi-pair two-way relaying with single-antenna mobile stations and a multi-antenna relay has been considered in [7], [8], [9] and different transceive filter designs based on zero-forcing block-diagonalization (ZFBD) are proposed to exploit self-interference cancellation. Considering multi-antenna mobile stations and exploiting the multiplexing gain increases the achievable sum rates. The authors of [10] investigate a pairwise communication of multi-antenna mobile stations via an intermediate multi-antenna relay. However, the introduced transceive filter approaches are based on mitigating self-interferences at RS without exploiting the capability of the nodes to subtract these interferences.

In this paper, a multi-pair two-way relaying scenario with multi-antenna mobile stations is considered. The bidirectional communications are performed via an intermediate half-duplex multi-antenna relay station. It is assumed that the mobile stations can subtract the back-propagated self-interference and that each mobile station transmits one data stream per antenna element to exploit the multiplexing gain. Different relay transceive filter design approaches which utilize the fact that the mobile stations can perform self-interference cancellation are introduced. First, a self-interference aware MMSE transceive filter is derived. Second, a multi-antenna MMSE extension of the zero-forcing block-diagonalization (ZFBD) based approaches is proposed and an upper bound for these approaches is given.

The paper is organized as follows. In Section II, the system model is given. Self-interference aware transceive filter designs are presented in Section III. In Section IV, the receive filters at the mobile stations are given. Simulation results in Section V confirm the analytical investigations and Section VI concludes the paper. [1]

II. System Model

As shown in Figure 1, K pairwise bidirectional communications via an intermediate multi-antenna relay station RS of

[1] 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 $\mathrm{tr}(\cdot)$, $\mathrm{diag}[\cdot]$, $\otimes$ denote the sum of the main diagonal elements of a matrix, the construction of a diagonal matrix with the elements contained in the vector and the Kronecker product of matrices, respectively. The operators $\Re[\cdot]$, $||\cdot||_2$ denote the real part of a scalar or a matrix and the Frobenius norm of a matrix, respectively. The 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 smaller 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.

$2K$ multi-antenna half-duplex mobile stations are considered. Mobile stations S_k and S_l form a bidirectional communication pair for $l = k - 1 + 2 \cdot \mathrm{mod}_2 k$, $k = 1, 2, ..., 2K$, i.e., S_1 and S_2, S_3 and S_4, ..., S_{2K-1} and S_{2K} form bidirectional communication pairs. The transmit power at each mobile station and at the relay station RS is limited by $P_{\mathrm{MS,max}}$ and $P_{\mathrm{RS,max}}$, respectively. Each mobile station is equipped with M antennas and simultaneously transmits M data streams. The number of antennas at RS is given by $L \geq M(2K-1)$.

The channel $\mathbf{H}_k \in \mathbb{C}^{L \times M}$ from S_k to RS is assumed to be constant during one transmission cycle of the two-way scheme and channel reciprocity is assumed. RS is assumed to have perfect channel state information (CSI) and the mobile stations have receive CSI and can subtract the back-propagated self-interference. All signals are assumed to be statistically independent and the noise at RS and at the mobile stations is assumed to be additive white Gaussian with variances $\sigma^2_{\mathrm{n,RS}}$ and σ^2_{n}, respectively. The system equations for two-way relaying are presented in the following where all mobile stations are simultaneously transmitting to RS in the first time slot. The transmitted symbols of S_k are contained in the vector $\mathbf{x}_{\mathrm{S}_k}$ and the transmit filter at S_k is given by $\mathbf{Q}_k = \sqrt{\frac{P_{\mathrm{MS,max}}}{M}} \cdot \mathbf{I}_M$. Thus, the received baseband signal at RS is given by

$$\mathbf{y}_{\mathrm{RS}} = \sum_{k=1}^{2K} \mathbf{H}_k \mathbf{Q}_k \mathbf{x}_{\mathrm{S}_k} + \mathbf{n}_{\mathrm{RS}}, \tag{1}$$

where $\mathbf{n}_{\mathrm{RS}}$ represents the complex white Gaussian noise vector at RS. RS linearly processes the received signal and the transceive filter at RS is given by

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

where $\widetilde{\mathbf{G}}$ 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. It is given by

$$\gamma = \sqrt{\frac{P_{\mathrm{RS,max}}}{\sum_{k=1}^{2K} ||\widetilde{\mathbf{G}}\mathbf{H}_k\mathbf{Q}_k||_2^2 + ||\widetilde{\mathbf{G}}||_2^2 \sigma^2_{\mathrm{n,RS}}}}. \tag{3}$$

The relay transmits the linearly processed version of $\mathbf{y}_{\mathrm{RS}}$ to all mobile stations. The received signal $\mathbf{y}_k$ using the receive filter $\mathbf{D}_k$ at mobile station S_k is given by

$$\mathbf{y}_{\mathrm{S}_k} = \mathbf{D}_k(\mathbf{H}_k^{\mathrm{T}} \mathbf{G} \mathbf{y}_{\mathrm{RS}} + \mathbf{n}_k), \tag{4}$$

where $\mathbf{n}_k$ represents the complex white Gaussian noise vector at S_k. The compositions of the receive signals are also illustrated in Figure 1. Each mobile station receives its intended useful signals, receives interference from the signals intended for the other mobile station termed inter-pair-interference, and receives back-propagated self-interference as well as noise. The inter-pair-interference has to be mitigated by the transceive filter at RS, but the back-propagated self-interference can be subtracted at each mobile station [1] assuming that $\mathbf{H}_k^{\mathrm{T}}\mathbf{G}\mathbf{H}_k$ is perfectly known at S_k. After self-interference cancellation, the received signal $\mathbf{y}_{\mathrm{S}_k-\mathrm{SI}}$ at S_k is

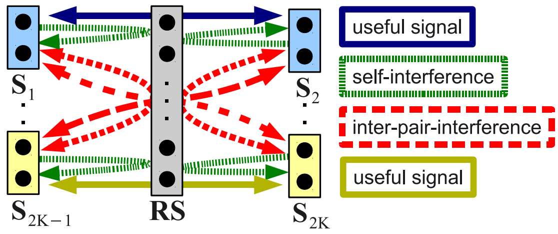

Fig. 1. Composition of useful signals and interferences in a bidirectional multi-pair two-way relaying scenario.

given by

$$\begin{aligned}\mathbf{y}_{\mathrm{S}_k-\mathrm{SI}} = \hat{\mathbf{x}}_{\mathrm{S}_l} =& \mathbf{D}_k \mathbf{H}_k^{\mathrm{T}} \mathbf{G} \sum_{j=1, j\neq k}^{2K} \mathbf{H}_j \mathbf{Q}_j \mathbf{x}_{\mathrm{S}_j} \\ &+ \mathbf{D}_k(\mathbf{H}_k^{\mathrm{T}} \mathbf{G} \mathbf{n}_{\mathrm{RS}} + \mathbf{n}_k),\end{aligned} \tag{5}$$

where $\hat{\mathbf{x}}_{\mathrm{S}_l}$ is the estimate of $\mathbf{x}_{\mathrm{S}_l}$ at mobile station S_k which bidirectionally communicates with S_l. The signal, interference and noise covariance matrices after self-interference cancellation for the transmission from S_k to S_l are given by

$$\begin{aligned}\mathbf{A}^{\mathrm{S}_k} &= \mathbf{H}_l^{\mathrm{T}} \mathbf{G} \mathbf{H}_k \mathbf{Q}_k \mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}} \mathbf{Q}_k^{\mathrm{H}} \mathbf{H}_k^{\mathrm{H}} \mathbf{G}^{\mathrm{H}} \mathbf{H}_l^{*}, \\ \mathbf{B}^{\mathrm{S}_k} &= \mathbf{H}_l^{\mathrm{T}} \mathbf{G} \left(\sum_{j=1, j\neq k,l}^{2K} \mathbf{H}_j \mathbf{Q}_j \mathbf{R}_{\mathbf{x}_{\mathrm{S}_j}} \mathbf{Q}_j^{\mathrm{H}} \mathbf{H}_j^{\mathrm{H}} \right) \mathbf{G}^{\mathrm{H}} \mathbf{H}_l^{*}, \\ \mathbf{C}^{\mathrm{S}_k} &= \mathbf{H}_l^{\mathrm{T}} \mathbf{G} \mathbf{R}_{\mathbf{n}_{\mathrm{RS}}} \mathbf{G}^{\mathrm{H}} \mathbf{H}_l^{*} + \mathbf{R}_{\mathbf{n}_{\mathrm{S}_k}},\end{aligned} \tag{6}$$

respectively, with $\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}$ the signal covariance matrix of $\mathbf{x}_{\mathrm{S}_k}$ and $\mathbf{R}_{\mathbf{n}_{\mathrm{RS}}}$, $\mathbf{R}_{\mathbf{n}_{\mathrm{S}_l}}$ the noise covariance matrices at RS and S_l, respectively.

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

$$C_{\mathrm{S}_k} = \frac{1}{2} \log_2 |(\mathbf{I}_M + \mathbf{A}^{\mathrm{S}_k}(\mathbf{B}^{\mathrm{S}_k} + \mathbf{C}^{\mathrm{S}_k})^{-1})|, \tag{7}$$

and the sum rate C_{sum} is given by

$$C_{\mathrm{sum}} = \sum_{k=1}^{2K} C_{\mathrm{S}_k}. \tag{8}$$

III. Transceive Filter Design at RS

The achievable sum rate C_{sum} (8) for the considered multi-user multi-antenna scenario under the given transmit power constraints shall be maximized. The sum rate maximization is a non-convex problem and an analytical solution cannot be obtained. To tackle this problem, different transceive filter approaches at RS are investigated in this section.

First, a self-interference aware MMSE transceive filter is derived. For the derivation of this transceive filter, the transmit and receive filters at the mobile stations are assumed to be fixed to obtain a convex problem. Thus, an analytical MMSE filter solution can be derived. Second, a multi-antenna MMSE extension of the ZFBD based approaches is proposed and an upper bound for these approaches is given.

A. Self-interference aware MMSE transceive filter

In the following, a self-interference aware MMSE transceive filter termed MMSE-SI is derived. For the derivation of the MMSE-SI filter, the error caused by self-interference is removed in the equations for the mean square error (MSE) so that back-propagated self-interference is only considered in the power constraint at RS and is not intentionally suppressed by the transceive filter design. The general equation for the transceive filter design at RS is given by

$$\mathbf{G} = \arg\min_{\mathbf{G}} \mathrm{E}\left\{\sum_{k=1}^{2K} \|\mathbf{x}_{\mathrm{S}_k} - \hat{\mathbf{x}}_{\mathrm{S}_k}\|_2^2\right\}. \tag{9}$$

The MSE for the transmission from S_k to S_l is given by

$$\begin{aligned}
&\mathrm{E}\left\{\|\mathbf{x}_{\mathrm{S}_k} - \hat{\mathbf{x}}_{\mathrm{S}_k}\|_2^2\right\} \\
&= \mathrm{tr}\left(\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\right) - 2\Re\left[\mathrm{tr}\left(\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\mathbf{H}_{\mathrm{k}}\mathbf{Q}_k\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\right)\right] \\
&+ \mathrm{tr}\left(\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\mathbf{H}_k\mathbf{Q}_k\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\mathbf{Q}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\mathbf{G}^{\mathrm{H}}\mathbf{H}_l^{*}\mathbf{D}_l^{\mathrm{H}}\right) \\
&+ \sum_{j=1, j\neq k,l}^{2K} \mathrm{tr}\left(\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\mathbf{H}_j\mathbf{Q}_j\mathbf{R}_{\mathbf{x}_{\mathrm{S}_j}}\mathbf{Q}_j^{\mathrm{H}}\mathbf{H}_j^{\mathrm{H}}\mathbf{G}^{\mathrm{H}}\mathbf{H}_l^{*}\mathbf{D}_l^{\mathrm{H}}\right) \\
&+ \mathrm{tr}\left(\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\mathbf{R}_{\mathbf{n}_{\mathrm{RS}}}\mathbf{G}^{\mathrm{H}}\mathbf{H}_l^{*}\mathbf{D}_l^{\mathrm{H}} + \mathbf{D}_l\mathbf{R}_{\mathbf{n}_{\mathrm{S}k}}\mathbf{D}_l^{\mathrm{H}}\right).
\end{aligned} \tag{10}$$

The MSE of (9) in combination with the power constraint of RS results in a convex problem with respect to $\mathbf{G}$ for fixed transmit and receive filters at the mobile stations. This problem can be solved by using Lagrangian optimization. Let matrices $\boldsymbol{\Upsilon}^{(k)}$ and $\boldsymbol{\Upsilon}$ be given by

$$\boldsymbol{\Upsilon}^{(k)} = \mathbf{H}_k\mathbf{Q}_k\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\mathbf{Q}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}} + \frac{1}{2K-1}\mathbf{R}_{\mathbf{n}_{\mathrm{RS}}}, \tag{11a}$$

$$\boldsymbol{\Upsilon} = \sum_{k=1}^{2K}\mathbf{H}_k\mathbf{Q}_k\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\mathbf{Q}_k^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}} + \mathbf{R}_{\mathbf{n}_{\mathrm{RS}}}. \tag{11b}$$

Using matrices $\boldsymbol{\Upsilon}^{(k)}$ and $\boldsymbol{\Upsilon}$ of (11) in (9) and considering the power constraint at RS, the Lagrangian function with the Lagrangian multiplier η results in

$$L\left(\mathbf{G},\eta\right) = \sum_{k=1}^{2K} F(\mathbf{G},k) - \eta\left(\mathrm{tr}\left(\mathbf{G}\boldsymbol{\Upsilon}\mathbf{G}^{\mathrm{H}}\right) - P_{\mathrm{RS,max}}\right), \tag{12}$$

with

$$\begin{aligned}
F(\mathbf{G},k) = &\ \mathrm{tr}\left(\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\right) - 2\Re\left[\mathrm{tr}\left(\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\mathbf{H}_k\mathbf{Q}_k\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}\right)\right] \\
&+ \mathrm{tr}\left(\sum_{j=1, j\neq l}^{2K}\mathbf{D}_l\mathbf{H}_l^{\mathrm{T}}\mathbf{G}\boldsymbol{\Upsilon}^{(j)}\mathbf{G}^{\mathrm{H}}\mathbf{H}_l^{*}\mathbf{D}_l^{\mathrm{H}}\right) \\
&+ \mathrm{tr}\left(\mathbf{D}_l\mathbf{R}_{\mathbf{n}_{\mathrm{S}_l}}\mathbf{D}_l^{\mathrm{H}}\right).
\end{aligned} \tag{13a}$$

where $l = k-1+2\cdot\mathrm{mod}_2 k$. From the Lagrangian function, the Karush-Kuhn-Tucker (KKT) conditions can be derived:

$$\frac{\partial L}{\partial \mathbf{G}} = \sum_{k=1}^{2K} f(\mathbf{G},k) - \eta\ \mathbf{G}^{*}\boldsymbol{\Upsilon}^{\mathrm{T}} = \mathbf{0}, \tag{14a}$$

$$\eta\left(\mathrm{tr}\left(\mathbf{G}\boldsymbol{\Upsilon}\mathbf{G}^{\mathrm{H}}\right) - P_{\mathrm{RS,max}}\right) = 0, \tag{14b}$$

$$\begin{aligned}
\text{with}:\ f(\mathbf{G},k) = &-\mathbf{H}_l\mathbf{D}_l^{\mathrm{T}}\mathbf{R}_{\mathbf{x}_{\mathrm{S}_k}}^{\mathrm{T}}\mathbf{Q}_k^{\mathrm{T}}\mathbf{H}_k^{\mathrm{T}} \\
&+ \sum_{j=1, j\neq l}^{2K}\mathbf{H}_l\mathbf{D}_l^{\mathrm{T}}\mathbf{D}_l^{*}\mathbf{H}_l^{\mathrm{H}}\mathbf{G}^{*}\boldsymbol{\Upsilon}^{(j)^{\mathrm{T}}}.
\end{aligned} \tag{15}$$

The KKT conditions can be used to determine the optimal transceive filter according to (9), because the optimization problem is convex for fixed transmit and receive filters at the mobile stations. In the following, matrix $\mathbf{K}$ is defined as

$$\begin{aligned}
\mathbf{K} = &\sum_{k=1}^{2K}\sum_{j=1, j\neq k}^{2K}\left[\boldsymbol{\Upsilon}^{(j)^{\mathrm{T}}} \otimes \left(\mathbf{H}_k^{*}\mathbf{D}_k^{\mathrm{H}}\mathbf{D}_k\mathbf{H}_k^{\mathrm{T}}\right)\right] \\
&+ \left[\boldsymbol{\Upsilon}^{\mathrm{T}} \otimes \frac{1}{P_{\mathrm{RS,max}}}\mathrm{tr}\left(\sum_{k=1}^{2K}\mathbf{R}_{\mathbf{n}_{\mathrm{S}_k}}\right)\mathbf{I}_L\right].
\end{aligned} \tag{16}$$

Using Eqs. (2), (3) and (16), the MMSE-SI filter at RS which solves problem (9) is given by

$$\mathbf{G} = \gamma\cdot\mathrm{vec}_{L,L}^{-1}\left(\mathbf{K}^{-1}\ \mathrm{vec}\left(\sum_{k=1}^{2K}\mathbf{H}_k^{*}\mathbf{D}_k^{\mathrm{H}}\mathbf{R}_{\mathbf{x}_{\mathrm{S}_l}}\mathbf{Q}_l^{\mathrm{H}}\mathbf{H}_l^{\mathrm{H}}\right)\right),$$

with $l = k-1+2\cdot\mathrm{mod}_2 k.$ (17)

The derived MMSE-SI transceive filter at RS minimizes the MSE for given transmit and receive filters at the mobile stations. To effectively suppress inter-pair interference at the receivers it only requires $L \geq M(2K-1)$ antennas at RS compared to a conventional MMSE transceive filter which requires $L \geq 2KM$ antennas at RS.

B. Multi-antenna MMSE extension of ZFBD approaches

In the following, a multi-antenna MMSE extension of the ZFBD based approaches investigated in [7], [8] and [9] is proposed. Applying the ZFBD technique, which has been introduced for downlink spatial multiplexing in [11], to the two-way relay channel, the relay transceive filter $\widetilde{\mathbf{G}}$ can be described by

$$\widetilde{\mathbf{G}} = \sum_{j=1}^{K}\frac{1}{||\mathbf{G}_{\mathrm{TF},j}\mathbf{G}_{\mathrm{single},j}\mathbf{G}_{\mathrm{RF},j}||_2}\mathbf{G}_{\mathrm{TF},j}\mathbf{G}_{\mathrm{single},j}\mathbf{G}_{\mathrm{RF},j}, \tag{18}$$

where $\mathbf{G}_{\mathrm{TF},j}$ and $\mathbf{G}_{\mathrm{RF},j}$ are transmit and receive prefilters for the jth pair to remove the inter-pair interference and where $\mathbf{G}_{\mathrm{single},j}$ is a single-pair transceive filter for pair j. Instead of completely suppressing inter-pair interference, we propose to allow some inter-pair interference according to the MMSE principle. Thus, the noise enhancement at RS is decreased and therewith the achievable sum rate is increased.

Let $\tilde{\mathbf{H}}_{\mathbf{j}} = [\mathbf{H}_1, \mathbf{H}_2, ..., \mathbf{H}_{2j-2}, \mathbf{H}_{2j+1}, ..., \mathbf{H}_{2K}]$ denote the channel matrix of all users not belonging to the jth pair. Thus, the proposed MMSE prefilter design for Eq. (18) based on the

SVD $\tilde{\mathbf{H}}_j = \tilde{\mathbf{U}}_{\mathbf{j}}\tilde{\mathbf{S}}_{\mathbf{j}}\tilde{\mathbf{V}}_{\mathbf{j}}$ is given by

$$\mathbf{G}_{\mathrm{RF},j} = \left(\tilde{\mathbf{U}}_{\mathbf{j}}\mathbf{D}_{\mathrm{RF},j}\right)^H, \tag{19a}$$

$$\mathbf{G}_{\mathrm{TF},j} = \tilde{\mathbf{U}}_{\mathbf{j}}\mathbf{D}_{\mathrm{TF},j}, \tag{19b}$$

$$\text{with}: \ \mathbf{D}_{\mathrm{RF},j} = \left(\tilde{\mathbf{S}}_{\mathbf{j}}\tilde{\mathbf{S}}_j^T + \frac{\sigma^2_{\mathrm{n,RS}}}{P_{\mathrm{MS,max}}}\mathbf{I}_L\right)^{-\frac{1}{2}}, \tag{19c}$$

$$\mathbf{D}_{\mathrm{TF},j} = \left(\tilde{\mathbf{S}}_{\mathbf{j}}\tilde{\mathbf{S}}_j^T + \frac{\sigma^2_{\mathrm{n}}}{P_{\mathrm{RS}}}\mathbf{I}_L\right)^{-\frac{1}{2}}. \tag{19d}$$

The proposed prefilter design requires $L \geq M(2K-1)$ antennas at RS to effectively suppress inter-pair interferences at the receivers, but it is also applicable if the number of antennas at RS is lower.

The design of the single-pair transceive filter $\mathbf{G}_{\mathrm{single},j}$ of Eq. (18) is based on the equivalent receive channel $\mathbf{H}_{\mathrm{R},j} = \mathbf{G}_{\mathrm{RF},j}[\mathbf{H}_{2j-1}, \mathbf{H}_{2j}]$ and on the equivalent transmit channel $\mathbf{H}_{\mathrm{T},j} = [\mathbf{H}^{\mathrm{T}}_{2j}, \mathbf{H}^{\mathrm{T}}_{2j-1}]^{\mathrm{T}}\mathbf{G}_{\mathrm{TF},j}$ for the jth pair, $j = 1, 2, ..., K$. In the case of only considering single antenna mobile stations, one approach, termed Pairwise-MF in the following, is to choose $\mathbf{G}_{\mathrm{single},j} = \mathbf{H}^{\mathrm{H}}_{\mathrm{T},j}\mathbf{H}^{\mathrm{H}}_{\mathrm{R},j}$. Only the prefilter design of this approach differs from the ZFBD based "NC-SM C. Combining" approach introduced in [9].

For multi-antenna mobile stations, a self-interference aware single-pair transceive filter supporting the multiplexing of M data streams per mobile station should be applied for $\mathbf{G}_{\mathrm{single},j}$ to maximize the achievable sum rate, e.g., the gradient based approach of [5]. The self-interference aware MMSE-SI filter derived in the Section III-A can also be applied for each single-pair transceive filter $\mathbf{G}_{\mathrm{single},j}$. In this case, the mobile stations of the jth pair and the corresponding equivalent channels are considered for the calculation of the MMSE-SI single-pair transceive filter. This approach is termed BD-MMSE-SI in the following.

For performance comparison, an upper bound for the achievable sum rate can be derived based on the proposed prefilter design. First, to separate each pair, the prefilters are calculated according to Eq. (19a) and (19b). Second, it is assumed that the bidirectional communication of each pair is performed via two unidirectional relays. The two unidirectional relays equally share the overall relay transmit power and are affected by the same overall noise power as the single relay of the real system. Under these assumptions, the optimal unidirectional transceive filters given in [2] and [3] for unidirectional relaying can be applied for each direction of transmission. This upper bound is a non reachable upper bound for the average achievable sum rate over different Rayleigh fading channels as soon as the mobile stations are equipped with more than one antenna. It is termed BD-Bound in the following.

IV. Receive filters at the mobile stations

In Section III, MMSE based transceive filters at RS are presented assuming predefined transmit and receive filters at the mobile stations. However, in case of multi-antenna mobile stations, optimizing these filters with respect to the transceive filter at RS increases the achievable sum rates. In this section, an alternating optimization between the receive filters at the mobile stations and the transceive filter at RS is presented. For the receive filter design, the available CSI is used and MMSE receive filters based on the overall channel $\mathbf{H}_{\mathrm{S}_k,\mathrm{ov}} = \mathbf{H}^{\mathrm{T}}_k\mathbf{G}\mathbf{H}_l\mathbf{Q}_l$ are applied. Based on the derivations in [12], the filters are given by

$$\mathbf{D}_k = \mathbf{H}^{\mathrm{H}}_{\mathrm{S}_k,\mathrm{ov}}(\mathbf{H}_{\mathrm{S}_k,\mathrm{ov}}\mathbf{H}^{\mathrm{H}}_{\mathrm{S}_k,\mathrm{ov}} + \mathbf{N}_{\mathrm{S}_k})^{-1}, \tag{20}$$

with $\mathbf{N}_{\mathrm{S}_k} = \mathbf{R}_{\mathbf{n}_{\mathrm{S}_k}} + \mathbf{H}^{\mathrm{T}}_k\mathbf{G}\mathbf{R}_{\mathbf{n}_{\mathrm{RS}}}\mathbf{G}^{\mathrm{H}}\mathbf{H}^*_{\mathrm{k}}$ the noise matrix. Inter-pair interference is neglected in the receive filters, because considering inter-pair interference requires additional CSI. The alternating optimization is performed in three steps: First, the transceive filter at RS is calculated assuming unitary receive filters $\mathbf{D}_k = \mathbf{I}_M$. Second, the receive filters according to Eq. (20) are calculated. Third, an alternating optimization between the transceive filter at RS and the receive filters at the mobile stations is performed until convergence. Joint optimization with the transmit filters at the mobile stations requires additional CSI and is not considered in this paper.

V. Simulation results

In this section, numerical results on the achievable sum rates for the introduced transceive filter designs at RS are investigated. It is assumed that $P_{\mathrm{MS,max}} = P_{\mathrm{RS,max}}$, $\sigma^2_{\mathrm{RS}} = \sigma^2_{\mathrm{n}}$ and $K = 2$. For comparison, a conventional MMSE approach is used, which does not exploit self-interference cancellation for the design of $\mathbf{G}$. The path-loss on the i.i.d. Rayleigh fading channels is varied and is represented by an average receive signal to noise ratio (SNR) at RS in the figures.

The average achievable sum rates over different receive SNRs for a single-antenna scenario, $M = 1$, $L = 4$, are shown in Figure 2. The performance of the MMSE-SI transceive filter and the BD-MMSE-SI transceive filter at RS are the same and both achieve sum rates close to the BD-Bound. The performance gap between the Pairwise-MF transceive filter and the MMSE-SI transceive filter is small, but the performance of the NC-SM C. Combining approach is significantly worse for small up to medium SNR values, because this approach uses ZFBD to suppress all inter-pair interferences. The performance of the conventional MMSE approach is significantly worse for an increase in the SNR, because it does not exploit the capability of the mobile stations to perform self-interference cancellation.

The average achievable sum rates over different number L of antennas at RS for the single-antenna scenario, $M = 1$, $\mathrm{SNR} = 15\mathrm{dB}$, are shown in Figure 3. The performance of the MMSE-SI transceive filter and the BD-MMSE-SI transceive filter at RS are the same and both achieve sum rates close to the BD-Bound. For three and four antennas at RS, the NC-SM C. Combining approach performs worse than the Pairwise-MF approach, because for low number of antennas at RS, the noise enhancement due to using ZFBD increases. The performance gap between the conventional MMSE approach

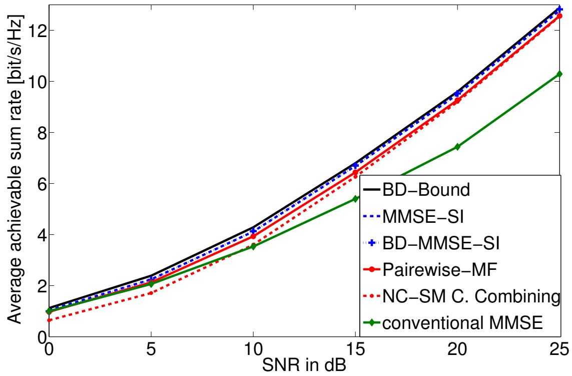

Fig. 2. Average achievable sum rates over different SNRs for single-antenna mobile stations, $M = 1$, $L = 4$.

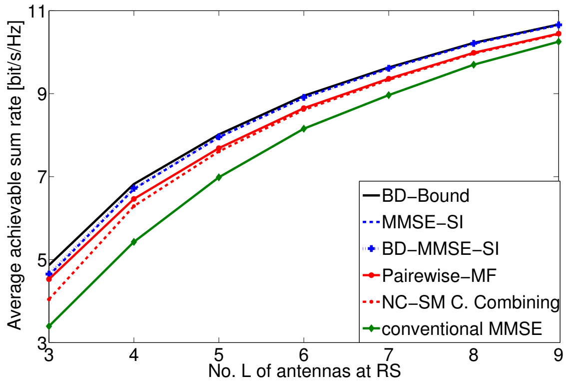

Fig. 3. Average achievable sum rates over number L of antennas at RS for $M = 1$, SNR=15dB.

and the other approaches increases which an decreasing number of antennas L at RS, because the performance loss due to additionally mitigating self-interferences at RS increases.

The average achievable sum rates over different SNRs for a scenario with $M = 2$ antennas at each mobile station and $L = 8$ antennas at RS are shown in Figure 4. The performance of the Pairwise-MF and the NC-SM C. Combining approach are not shown, because these approaches are not designed to support the multiplexing of two data streams per mobile station. The performance of the MMSE-SI transceive filter at RS which is alternately optimized with the receive filters at the mobile stations is termed MMSE-SI alternating. The performance is only slightly better than the performance of the MMSE-SI filter without alternating optimization termed MMSE-SI. The conventional MMSE filter performs worse due to not taking advantage of the capability of the mobile stations to perform self-interference cancellation. The achievable sum rates of the MMSE-SI transceive filter are close to the BD-Bound.

VI. Conclusions

Non-regenerative two-way relaying for a multi-pair multi-antenna scenario has been investigated. A self-interference aware MMSE transceive filter is derived and a multi-antenna MMSE extension of the zero-forcing block-diagonalization based approaches is proposed. The proposed MMSE-SI transceive filter requires less antennas at RS compared to a

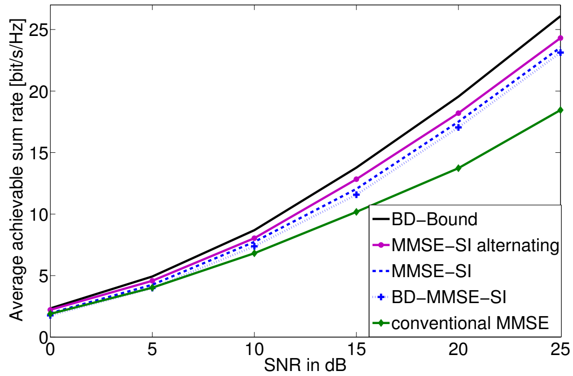

Fig. 4. Average achievable sum rates over different SNRs for multi-antenna mobile stations, $M = 2$, $L = 8$.

conventional MMSE filter and achieves significantly higher sum rates due to exploiting self-interference cancellation at the mobile stations for the transceive filter design at RS.

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