Spatial Loop Interference Suppression in Full-Duplex MIMO Relays

Taneli Riihonen, Stefan Werner, and Risto Wichman
SMARAD CoE and Department of Signal Processing and Acoustics
Helsinki University of Technology, P.O. Box 3000, FI-02015 TKK, Finland
Email: {taneli.riihonen, stefan.werner, risto.wichman}@tkk.fi

***Abstract*—The main technical problem in full-duplex relaying is to suppress the looping interference signal from relay transmission to relay reception. The earlier literature on the topic is mostly restricted to SISO channels. We take a step further and consider a system where the coverage of a MIMO transmission link is boosted with a two-hop full-duplex MIMO relay. First, we present a MIMO extension of SISO time-domain cancellation techniques based on subtraction of an estimated loop signal. We show how the loop interference can be suppressed in the spatial domain by applying multi-antenna techniques. The solution involves design of linear receive and transmit filters for the relay to improve the quality of the useful signal and to minimize the effect of the loop interference. We propose null space projection and minimum mean square error filters for spatial loop interference suppression as well as discuss shortly how to combine them with time-domain cancellation.**

I. Introduction

We consider a two-hop multi-antenna system in which a source (S) node (e.g., a base station) communicates with a destination (D) node (e.g, a user terminal) via an *infrastructure-based* relay (R) node as illustrated in Fig. 1. The relay is equipped with separated receive and transmit antenna arrays. For this type of setup, our recent studies [1], [2] have shown that a *full-duplex mode* is a spectrally efficient alternative for the widely-used *half-duplex mode*. This is because full-duplex relays receive and transmit simultaneously while the half-duplex mode allocates two channels for single end-to-end transmission. This paper concentrates on solving the fundamental, yet open, technical problem arising in full-duplex relays which is the mitigation of *loop interference* (LI) due to signal leakage from relay's transmission to its own reception.

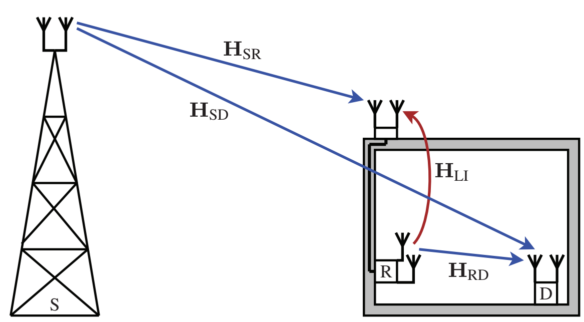

Fig. 1. Two-hop full-duplex multi-antenna relay link in a typical outdoor-to-indoor transmission scenario. The MIMO channels are represented by $\mathbf{H}_{\mathrm{SR}}$, $\mathbf{H}_{\mathrm{RD}}$, $\mathbf{H}_{\mathrm{LI}}$, and $\mathbf{H}_{\mathrm{SD}}$.

It is foreseeable that future wireless systems will utilize multi-antenna techniques and, in particular, spatial division multiplexing in the end-to-end links. Thus, relays will be equipped with antenna arrays as well to avoid a key-hole effect, i.e., squashing multiple spatial streams through a rank-one device. Some prototypes of full-duplex MIMO relays have already been developed, see [3], [4]. After solving the loop interference problem, such on-channel repeaters become a viable option for boosting cell coverage transparently. However, research on the effect of loop interference in full-duplex MIMO relays is so far limited: our literature search elicited few earlier ideas [5], [6] and recent studies [7]–[11] conducted in parallel with our work.

Although full-duplex relaying with a single antenna array is optimistically proposed in [9], the isolation offered by modern duplex circuits used in continuous-wave radars may not be sufficient for communication purposes. Thereby, we assume separated receive and transmit antenna arrays and classify the countermeasures as in [12]: physical isolation between antennas, antenna directivity (including spatial suppression schemes proposed herein), loop interference cancellation [13], [14], and relay gain control [15]. The target is to reduce the residual loop interference so that it can be regarded simply as additional noise. Consequently, our work facilitates usage of many full-duplex relaying schemes that are designed assuming perfect mitigation, see, e.g., [16], [17].

The loop interference is conventionally cancelled by estimating the interference signal and subtracting it from the relay input [13], [14]. These time-domain techniques almost exclusively deal with the case of SISO channels. Thereby, our first contribution is to summarize how earlier SISO cancellation schemes can be generalized for MIMO relays.

The increased degrees of freedom offered by the spatial domain open up a range of new solutions for loop interference mitigation. The main contribution of this paper is to exploit the antenna arrays for suppressing the loop interference. Thus, the relay may utilize the degrees of freedom provided by both the receive and transmit antennas to improve the link quality. We propose spatial suppression by using null space projection and minimum mean square error (MMSE) filters. A combination of time-domain cancellation and spatial suppression can be also used. Finally, our simulation results verify that all the discussed schemes mitigate interference significantly, but they are sensitive to channel estimation errors.

II. System Model

We denote that the source and the relay have $N_{\text{S,tx}}$ and $N_{\text{R,tx}}$ transmit antennas, respectively, and the relay and the destination have $N_{\text{R,rx}}$ and $N_{\text{D,rx}}$ receive antennas, respectively. At time instant i, the source transmits $N_{\text{S,tx}} \times 1$ signal vector $\mathbf{x}[i]$, and the relay transmits $N_{\text{R,tx}} \times 1$ signal vector $\mathbf{t}[i]$ while it simultaneously receives $N_{\text{R,rx}} \times 1$ signal vector $\mathbf{r}[i]$. This creates a feedback loop from the relay output to the relay input. For a two-hop system, the received signals in the relay and in the destination can then be expressed as

$$\begin{aligned}\mathbf{r}[i] &= \mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{H}_{\text{LI}}\mathbf{t}[i] + \mathbf{n}_{\text{R}}[i], \\ \mathbf{y}[i] &= \mathbf{H}_{\text{RD}}\mathbf{t}[i] + \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i],\end{aligned} \tag{1}$$

in which $\mathbf{H}_{\text{SR}}$, $\mathbf{H}_{\text{LI}}$, $\mathbf{H}_{\text{RD}}$ and $\mathbf{H}_{\text{SD}}$ are the respective $N_{\text{R,rx}} \times N_{\text{S,tx}}$ source–relay, $N_{\text{R,rx}} \times N_{\text{R,tx}}$ loop interference (LI), $N_{\text{D,rx}} \times N_{\text{R,tx}}$ relay–destination and $N_{\text{D,rx}} \times N_{\text{S,tx}}$ source–destination channel matrices. Additive noise vectors in the relay and in the destination are given by $\mathbf{n}_{\text{R}}[i]$ and $\mathbf{n}_{\text{D}}[i]$.

In the most generic form, a relaying protocol can be defined as a function that generates an output sample based on the sequence of input samples:

$$\mathbf{t}[i] = f(\mathbf{r}[i-\tau], \mathbf{r}[i-(\tau+1)], \mathbf{r}[i-(\tau+2)], \ldots), \tag{2}$$

in which the processing delay is $\tau > 0$ samples. We try keep the following analysis on a general level such that the proposed interference mitigation schemes can be applied with most of the readily available relaying protocols. Let us recall the following example protocols for the purpose of illustration.

Example protocol I: A repetition-based decode-and-forward protocol uses the same codebook in both hops while proper rate adaptation guarantees that the relay can decode its input signal without errors. Thus, $\mathbf{t}[i] = f(\mathbf{r}[i-\tau], \mathbf{r}[i-(\tau+1)], \mathbf{r}[i-(\tau+2)], \ldots) = \mathbf{x}[i-\tau]$ and the signal model becomes

$$\begin{aligned}\mathbf{r}[i] &= \mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{H}_{\text{LI}}\mathbf{x}[i-\tau] + \mathbf{n}_{\text{R}}[i], \\ \mathbf{y}[i] &= \mathbf{H}_{\text{RD}}\mathbf{x}[i-\tau] + \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i].\end{aligned} \tag{3}$$

In spite of the assumption on error-free decoding in the relay, the looping signal is considered harmful, because it reduces the achievable rate in the first hop.

Example protocol II: An amplify-and-forward protocol filters the input signal with $N_{\text{R,tx}} \times N_{\text{R,rx}}$ matrix $\mathbf{B}$. Constraint $\max|\text{eig}(\mathbf{H}_{\text{LI}}\mathbf{B})| < 1$ is needed in order to prevent relay oscillation and to guarantee bounded transmit power. Now $\mathbf{t}[i] = f(\mathbf{r}[i-\tau]) = \mathbf{B}\mathbf{r}[i-\tau]$, and the signal model becomes

$$\begin{aligned}\mathbf{r}[i] &= \sum_{j=0}^{\infty}(\mathbf{H}_{\text{LI}}\mathbf{B})^{j}\left(\mathbf{H}_{\text{SR}}\mathbf{x}[i-j\tau] + \mathbf{n}_{\text{R}}[i-j\tau]\right) \\ \mathbf{y}[i] &= \mathbf{H}_{\text{SD}}\mathbf{x}[i] + \mathbf{H}_{\text{RD}}\mathbf{B}\sum_{j=1}^{\infty}(\mathbf{H}_{\text{LI}}\mathbf{B})^{j-1}\mathbf{H}_{\text{SR}}\mathbf{x}[i-j\tau] \\ &\quad + \mathbf{H}_{\text{RD}}\mathbf{B}\sum_{j=1}^{\infty}(\mathbf{H}_{\text{LI}}\mathbf{B})^{j-1}\mathbf{n}_{\text{R}}[i-j\tau] + \mathbf{n}_{\text{D}}[i].\end{aligned} \tag{4}$$

The end-to-end signal is degraded, because the feedback loop channel causes both noise amplification and infinitely repeating echo signals. Thus, gain control is needed [12], [15].

The relay needs to know channel $\mathbf{H}_{\text{LI}}$ in order to enable loop interference mitigation. The channel state information can be obtained by adaptive filtering or pilot-based estimation techniques. In this paper, we simply denote that there is some random estimation error $\mathbf{\Delta\tilde{H}}_{\text{LI}}$ such that estimate $\tilde{\mathbf{H}}_{\text{LI}}$ differs from true channel value $\mathbf{H}_{\text{LI}} = \tilde{\mathbf{H}}_{\text{LI}} + \mathbf{\Delta\tilde{H}}_{\text{LI}}$. This allows us to avoid restricting the analysis to any particular implementation.

Special Case: No Processing Delay

The common limitation in earlier literature [7], [8], [10] is to neglect the relay processing delay ($\tau = 0$). To emphasize the novelty of our work that explicitly accounts for the delay, let us briefly summarize the behavior of the two example protocols without the processing delay.

Example protocol I: With the repetition-based decode-and-forward protocol, the signal model reduces from (3) to

$$\begin{aligned}\mathbf{r}[i] &= (\mathbf{H}_{\text{SR}} + \mathbf{H}_{\text{LI}})\mathbf{x}[i] + \mathbf{n}_{\text{R}}[i], \\ \mathbf{y}[i] &= (\mathbf{H}_{\text{RD}} + \mathbf{H}_{\text{SD}})\mathbf{x}[i] + \mathbf{n}_{\text{D}}[i].\end{aligned} \tag{5}$$

Hence, the feedback loop does not cause any interference, but instead amplifies the desired relay input signal. Moreover, there is severe causality problem involving the practical implementations of this theoretical system, because it may be impossible to decode, re-encode and transmit a signal sample before it has been completely received.

Example protocol II: The signal model of the amplify-and-forward relay link reduces from (1) to

$$\mathbf{r}[i] = (\mathbf{I} - \mathbf{H}_{\text{LI}}\mathbf{B})^{-1}(\mathbf{H}_{\text{SR}}\mathbf{x}[i] + \mathbf{n}_{\text{R}}[i]). \tag{6}$$

In order to the inverse to exist, we assume that all $\text{eig}(\mathbf{H}_{\text{LI}}\mathbf{B}) \neq 1$. The condition is needed in order to avoid transmitting a signal that cancels the useful signal in the relay input in some dimension. In fact, this anomaly appears only due to the neglected processing delay. We see that the system is now actually equivalent to an interference-free amplify-and-forward relay link with end-to-end signal model

$$\mathbf{y}[i] = \left(\mathbf{H}_{\text{SD}} + \mathbf{H}_{\text{RD}}\hat{\mathbf{B}}\mathbf{H}_{\text{SR}}\right)\mathbf{x}[i] + \mathbf{H}_{\text{RD}}\hat{\mathbf{B}}\mathbf{n}_{\text{R}}[i] + \mathbf{n}_{\text{D}}[i], \tag{7}$$

in which the effective amplification factor of the relay is given by $\hat{\mathbf{B}} = \mathbf{B}(\mathbf{I} - \mathbf{H}_{\text{LI}}\mathbf{B})^{-1}$. Earlier literature has studied such systems effectively, and provides various solutions for designing $\hat{\mathbf{B}}$. Assuming that $\mathbf{H}_{\text{LI}}$ is known, almost any desired effective amplification $\hat{\mathbf{B}}$ can then be implemented simply by selecting

$$\mathbf{B} = \hat{\mathbf{B}}(\mathbf{I} + \mathbf{H}_{\text{LI}}\hat{\mathbf{B}})^{-1} \tag{8}$$

as pointed out in [10]. Thereby, the loop interference cannot be considered harmful in the delay-free case.

The above examples show that the loop signal is not interference in the delay-free case, and, thus, there is no need for mitigation techniques. Furthermore, with $\tau = 0$, the narrowband system model with frequency-flat channels contradicts with practical implementations. In the context of an OFDM system, the narrowband assumption is true for a single subcarrier, but then $\tau > 0$ is required because a complete OFDM symbol needs to be received and demodulated before the subcarriers can be processed in the frequency domain.

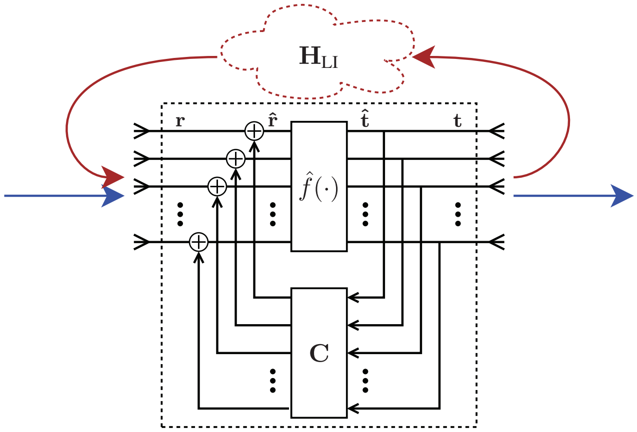

Fig. 2. Conventional time-domain loop interference cancellation in a full-duplex MIMO relay by subtracting an estimate of the interference signal.

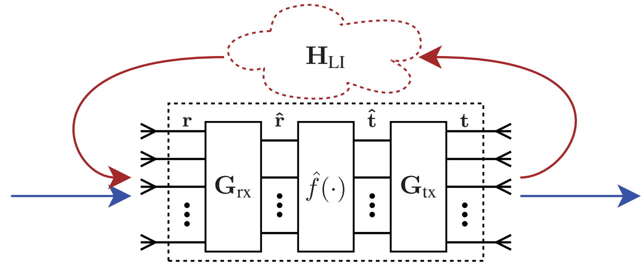

Fig. 3. Spatial loop interference suppression in a full-duplex MIMO relay by using linear receive and transmit filters.

III. Conventional Interference Cancellation

Time-domain loop cancellation is based on the reasonable assumption that the relay always knows its own transmitted signal. Then the straightforward MIMO extension of the earlier SISO cancellation schemes [13], [14] can be implemented as illustrated in Fig. 2: an estimate of the interference signal vector is subtracted from the relay input signal vector.

After estimation of the loop channel, the cancellation filter can be selected as $\mathbf{C} = -\tilde{\mathbf{H}}_{\mathrm{LI}}$. This yields the following relay input and output signals after cancellation:

$$\begin{aligned} \mathbf{t}[i] &= \hat{\mathbf{t}}[i], && (9) \\ \hat{\mathbf{r}}[i] &= \mathbf{r}[i] + \mathbf{C}\mathbf{t}[i] = \mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] + \hat{\mathbf{H}}_{\mathrm{LI}}\hat{\mathbf{t}}[i] + \mathbf{n}_{\mathrm{R}}[i]. \end{aligned}$$

Due to imperfect channel estimation, the residual loop interference channel shown above is

$$\hat{\mathbf{H}}_{\mathrm{LI}} = \mathbf{H}_{\mathrm{LI}} + \mathbf{C} = \boldsymbol{\Delta}\tilde{\mathbf{H}}_{\mathrm{LI}}. \qquad (10)$$

If cancellation works properly, the residual loop interference can be regarded as mere additional noise and the actual relay protocol $\hat{f}(\cdot)$ can be tailored for the end-to-end transmission by neglecting the interference. However, the drawback of this solution is that it does not exploit the spatial domain, e.g., low rank of $\mathbf{H}_{\mathrm{LI}}$ cannot be exploited to improve the performance.

IV. Spatial Interference Suppression

As a solution to exploit the extra degrees of freedom offered by the spatial domain, we propose that the relay applies $N_{\mathrm{R,tx}} \times \hat{N}_{\mathrm{R,tx}}$ transmit weight matrix $\mathbf{G}_{\mathrm{tx}}$ and $\hat{N}_{\mathrm{R,rx}} \times N_{\mathrm{R,rx}}$ receive weight matrix $\mathbf{G}_{\mathrm{rx}}$ as shown in Fig. 3. Without loss of generality, we can assume that $\hat{N}_{\mathrm{R,tx}} \leq N_{\mathrm{R,tx}}$, $\hat{N}_{\mathrm{R,rx}} \leq N_{\mathrm{R,rx}}$, because the end-to-end transmission cannot be improved by artificially increasing the number of dimensions. The transmitted and received signals in the relay become

$$\begin{aligned} \mathbf{t}[i] &= \mathbf{G}_{\mathrm{tx}}\hat{\mathbf{t}}[i], && (11) \\ \hat{\mathbf{r}}[i] &= \mathbf{G}_{\mathrm{rx}}\mathbf{r}[i] = \mathbf{G}_{\mathrm{rx}}\mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] + \hat{\mathbf{H}}_{\mathrm{LI}}\hat{\mathbf{t}}[i] + \mathbf{G}_{\mathrm{rx}}\mathbf{n}_{\mathrm{R}}[i], \end{aligned}$$

in which the residual loop interference channel is

$$\hat{\mathbf{H}}_{\mathrm{LI}} = \mathbf{G}_{\mathrm{rx}}\mathbf{H}_{\mathrm{LI}}\mathbf{G}_{\mathrm{tx}} = \mathbf{G}_{\mathrm{rx}}\tilde{\mathbf{H}}_{\mathrm{LI}}\mathbf{G}_{\mathrm{tx}} + \mathbf{G}_{\mathrm{rx}}\boldsymbol{\Delta}\tilde{\mathbf{H}}_{\mathrm{LI}}\mathbf{G}_{\mathrm{tx}}. \qquad (12)$$

Again the actual relay protocol $\hat{f}(\cdot)$ can be tailored for the end-to-end transmission scheme by neglecting the loop interference. In the following, we present and compare two different solutions, namely zero-forcing of loop interference and MMSE type of pre- or post-whitening. Furthermore, we discuss how spatial suppression can be combined with time-domain cancellation.

A. *Zero Forcing of Loop Interference*

When the loop interference is dominating, a zero forcing (ZF) approach, i.e., a null space projection, is an efficient solution which requires channel state information only on $\mathbf{H}_{\mathrm{LI}}$. With ZF, $\mathbf{G}_{\mathrm{rx}}$ and $\mathbf{G}_{\mathrm{tx}}$ are selected in such a way that $\hat{\mathbf{t}}[i]$ is suppressed completely from $\hat{\mathbf{r}}[i]$, i.e.,

$$\mathbf{G}_{\mathrm{rx}}\tilde{\mathbf{H}}_{\mathrm{LI}}\mathbf{G}_{\mathrm{tx}} = \mathbf{0}. \qquad (13)$$

If there is no channel estimation error, this condition transforms the $N_{\mathrm{R,tx}} \times N_{\mathrm{R,rx}}$ relay to an $\hat{N}_{\mathrm{R,tx}} \times \hat{N}_{\mathrm{R,rx}}$ relay without loop interference.

Let us recall the singular value decomposition of $\tilde{\mathbf{H}}_{\mathrm{LI}}$:

$$\tilde{\mathbf{H}}_{\mathrm{LI}} = \tilde{\mathbf{U}}\tilde{\boldsymbol{\Sigma}}\tilde{\mathbf{V}}^H = [\tilde{\mathbf{U}}_{(1)}|\tilde{\mathbf{U}}_{(0)}]\tilde{\boldsymbol{\Sigma}}[\tilde{\mathbf{V}}_{(1)}|\tilde{\mathbf{V}}_{(0)}]^H \qquad (14)$$

in which $\tilde{\mathbf{U}}_{(0)}$ and $\tilde{\mathbf{V}}_{(0)}$ denote the basis vectors associated with zero singular values. The selection of the weight matrices is flexible in ZF, and depends highly on whether $\mathbf{G}_{\mathrm{rx}}$ and $\mathbf{G}_{\mathrm{tx}}$ are designed separately or jointly.

For designing the filters separately, the row space of $\mathbf{G}_{\mathrm{rx}}$ should be in the left null space of $\tilde{\mathbf{H}}_{\mathrm{LI}}$, i.e., $\mathbf{G}_{\mathrm{rx}} = \tilde{\mathbf{U}}_{(0)}^H$ or the column space of $\mathbf{G}_{\mathrm{tx}}$ should be in the null space of $\tilde{\mathbf{H}}_{\mathrm{LI}}$, i.e., $\mathbf{G}_{\mathrm{tx}} = \tilde{\mathbf{V}}_{(0)}$. Let $\mathbf{X}^+$ denote the Moore-Penrose pseudoinverse of $\mathbf{X}$ for which $\mathbf{X}\mathbf{X}^+\mathbf{X} = \mathbf{X}$ by definition. For zero-forcing, we can thereby equivalently apply projection matrices as

$$\mathbf{G}_{\mathrm{rx}} = \mathbf{I} - \tilde{\mathbf{H}}_{\mathrm{LI}}\tilde{\mathbf{H}}_{\mathrm{LI}}^+, \qquad (15)$$

$$\mathbf{G}_{\mathrm{tx}} = \mathbf{I} - \tilde{\mathbf{H}}_{\mathrm{LI}}^+\tilde{\mathbf{H}}_{\mathrm{LI}}. \qquad (16)$$

These projection matrices lead effectively to the same mapping, but $\hat{N}_{\mathrm{R,rx}} = N_{\mathrm{R,rx}}$ or $\hat{N}_{\mathrm{R,tx}} = N_{\mathrm{R,tx}}$. The dimensions of $\mathbf{G}_{\mathrm{rx}}$ and $\mathbf{G}_{\mathrm{tx}}$ depend on the rank of $\tilde{\mathbf{H}}_{\mathrm{LI}}$. For example, full rank of $\mathbf{H}_{\mathrm{LI}}$ leads inevidently to $\mathbf{G}_{\mathrm{rx}} = \mathbf{0}$ or $\mathbf{G}_{\mathrm{tx}} = \mathbf{0}$ in above.

If one filter is already chosen, the other filter can be designed using a projection matrix as

$$\mathbf{G}_{\text{rx}} = \mathbf{I} - \tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}}\left(\tilde{\mathbf{H}}_{\text{LI}}\mathbf{G}_{\text{tx}}\right)^{+}, \tag{17}$$

$$\mathbf{G}_{\text{tx}} = \mathbf{I} - \left(\mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}\right)^{+}\mathbf{G}_{\text{rx}}\tilde{\mathbf{H}}_{\text{LI}}. \tag{18}$$

However, joint design offers even more degrees of freedom: if $\mathbf{G}_{\text{rx}}$ and $\mathbf{G}_{\text{tx}}$ are designed jointly, the row space of $\mathbf{G}_{\text{rx}}$ can be set to be located in the left null space of $\mathbf{H}_{\text{LI}}\mathbf{G}_{\text{tx}}$ by selecting the basis vectors for $\mathbf{G}_{\text{rx}}$ and $\mathbf{G}_{\text{tx}}$ such that they correspond to different or zero singular values. This allows supporting more spatial input and output streams in the relay.

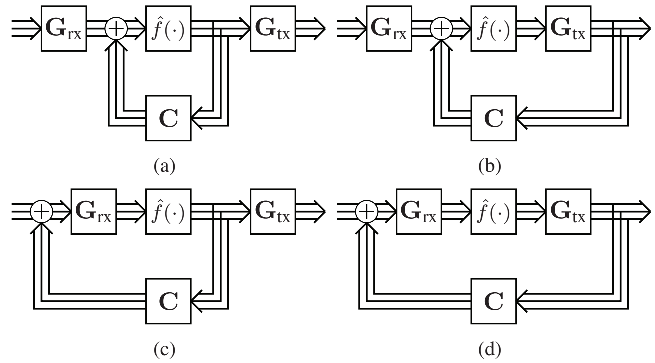

Fig. 4. Four variations for combining conventional interference cancellation and spatial suppression.

B. *MMSE Filtering*

Time-domain cancellation and spatial null space projection aim merely at minimizing the effect of loop interference. However, the degrees of freedom in the spatial domain allow for more sophisticated approach in which the useful signal power is also improved. In the following, we let $\mathcal{E}\{\cdot\}$ denote the expectation over signal and noise distributions.

Noting that the desired relay input signal is $\mathbf{H}_{\text{SR}}\mathbf{x}$ while $\hat{\mathbf{r}}$ contains also residual loop interference and noise, the mean square error (MSE) matrix can be formulated as

$$\begin{aligned}\mathbf{M} &= \mathcal{E}\left\{\left(\mathbf{H}_{\text{SR}}\mathbf{x} - \hat{\mathbf{r}}\right)\left(\mathbf{H}_{\text{SR}}\mathbf{x} - \hat{\mathbf{r}}\right)^{H}\right\} \qquad (19)\\ &= \left(\mathbf{I} - \mathbf{G}_{\text{rx}}\right)\mathbf{H}_{\text{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\text{SR}}^{H}\left(\mathbf{I} - \mathbf{G}_{\text{rx}}^{H}\right) + \hat{\mathbf{H}}_{\text{LI}}\mathbf{R}_{\hat{\mathbf{t}}}\hat{\mathbf{H}}_{\text{LI}}^{H} + \mathbf{R}_{\hat{\mathbf{n}}_{\text{R}}}.\end{aligned}$$

The signal and noise covariance matrices are here given by $\mathbf{R}_{\mathbf{x}} = \mathcal{E}\{\mathbf{x}\mathbf{x}^{H}\}$, $\mathbf{R}_{\hat{\mathbf{t}}} = \mathcal{E}\{\hat{\mathbf{t}}\hat{\mathbf{t}}^{H}\}$, $\mathbf{R}_{\mathbf{t}} = \mathcal{E}\{\mathbf{t}\mathbf{t}^{H}\} = \mathbf{G}_{\text{tx}}\mathbf{R}_{\hat{\mathbf{t}}}\mathbf{G}_{\text{tx}}^{H}$, $\mathbf{R}_{\mathbf{n}_{\text{R}}} = \mathcal{E}\{\mathbf{n}_{\text{R}}\mathbf{n}_{\text{R}}^{H}\}$, and $\mathbf{R}_{\hat{\mathbf{n}}_{\text{R}}} = \mathbf{G}_{\text{rx}}\mathbf{R}_{\mathbf{n}_{\text{R}}}\mathbf{G}_{\text{rx}}^{H}$.

The minimum MSE (MMSE) relay receive matrix can be derived from the condition $\frac{\partial}{\partial \mathbf{G}_{\text{rx}}}\text{tr}\{\mathbf{M}\} = \mathbf{0}$, in which $\text{tr}\{\cdot\}$ denotes the matrix trace, yielding

$$\mathbf{G}_{\text{rx}} = \mathbf{H}_{\text{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\text{SR}}^{H}\left(\mathbf{H}_{\text{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\text{SR}}^{H} + \tilde{\mathbf{H}}_{\text{LI}}\mathbf{R}_{\mathbf{t}}\tilde{\mathbf{H}}_{\text{LI}}^{H} + \mathbf{R}_{\mathbf{n}_{\text{R}}}\right)^{-1}. \tag{20}$$

Note that, before using the above expression, the relay transmit filter $\mathbf{G}_{\text{tx}}$ needs to be chosen and the relay needs to know $\mathbf{H}_{\text{SR}}$.

At the transmit side, the condition $\frac{\partial}{\partial \mathbf{G}_{\text{tx}}}\text{tr}\{\mathbf{M}\} = \mathbf{0}$ to minimize MSE reduces to the zero-forcing condition given in (13). Therefore, the evident order for joint filter design is to first implement the transmit filter using (16), or to minimize interference at the transmit side using any scheme, and then design the receive filter using (20).

C. *Combining Cancellation and Spatial Suppression*

It should be noted that time-domain cancellation and spatial suppression are not mutually exclusive schemes. Residual loop interference after one scheme can be further reduced by applying the other scheme. This fact motivates for the four different variations to combine cancellation and spatial suppression illustrated in Fig. 4. Only variation (a) is considered in earlier literature [7]. The performance of the variations is not the same, because they result in different residual loop interference channels:

$$\hat{\mathbf{H}}_{\text{LI}} = \begin{cases} \mathbf{G}_{\text{rx}}\mathbf{H}_{\text{LI}}\mathbf{G}_{\text{tx}} + \mathbf{C}, & \text{variation (a)},\\ (\mathbf{G}_{\text{rx}}\mathbf{H}_{\text{LI}} + \mathbf{C})\mathbf{G}_{\text{tx}}, & \text{variation (b)},\\ \mathbf{G}_{\text{rx}}(\mathbf{H}_{\text{LI}}\mathbf{G}_{\text{tx}} + \mathbf{C}), & \text{variation (c)},\\ \mathbf{G}_{\text{rx}}(\mathbf{H}_{\text{LI}} + \mathbf{C})\mathbf{G}_{\text{tx}}, & \text{variation (d)}. \end{cases} \tag{21}$$

It is expected that the practical implementation of variations (a) and (d) is the most straightforward, because the two mitigation techniques can be decoupled. In variation (a), spatial interference suppression is first applied, and then the residual interference given by (12) can be mitigated by loop interference cancellation. The order is the opposite for variation (d) which applies first the conventional loop interference cancellation and then residual interference given by (10) is further reduced by spatial suppression.

V. Simulation Results

We next demonstrate the mitigation techniques by simulating uncoded bit error rate (BER) in a decode-and-forward relay. The relay extends the range of ideally pre-coded two-stream end-to-end QPSK transmission with $N_{\text{S,tx}} = N_{\text{D,rx}} = 2$. The channels are independently Rayleigh fading and additive noise is white and Gaussian. The parameters are the signal-to-noise ratio (SNR) of the first hop excluding the loop interference and the relay input signal-to-interference ratio (SIR), which define the loop interference power before mitigation.

Firstly, simulated BERs are illustrated in Fig. 5 in terms of the first hop SNR when the loop interference channel is perfectly known in mitigation ($\boldsymbol{\Delta}\tilde{\mathbf{H}}_{\text{LI}} = \mathbf{0}$). Without mitigation of the loop interference, BER converges to a floor value defined by the input SIR preventing reliable communication. The performance of the spatial suppression schemes depend essentially on the rank of the loop interference channel. The extra dimensions that are not reserved for mitigation of loop interference offer beamforming gain for the useful signal.

Secondly, simulated BERs are illustrated in Fig. 6 in terms of the relative channel estimation error, i.e, the ratio of the mean square estimation error to the mean channel gain. The main observation is that the non-ideal channel estimation is the major limitation to prevent perfect mitigation.

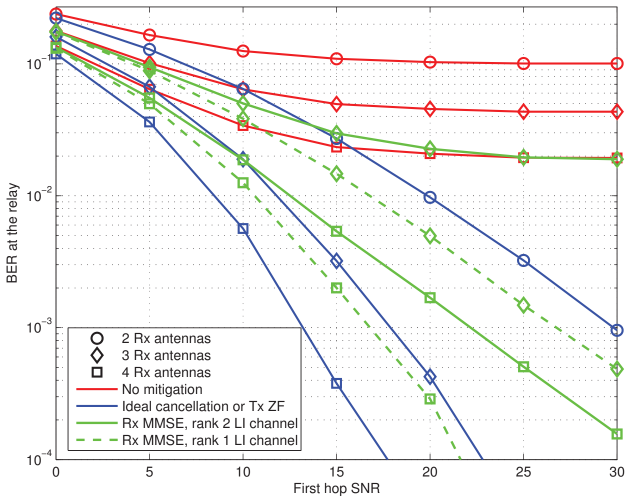

Fig. 5. Uncoded bit error rate at a decode-and-forward relay for two-stream QPSK transmission. Estimation of the loop interference channel is ideal and the transmit powers of all compared schemes are normalized to the same value. The signal-to-interference ratio in the relay input is 10dB.

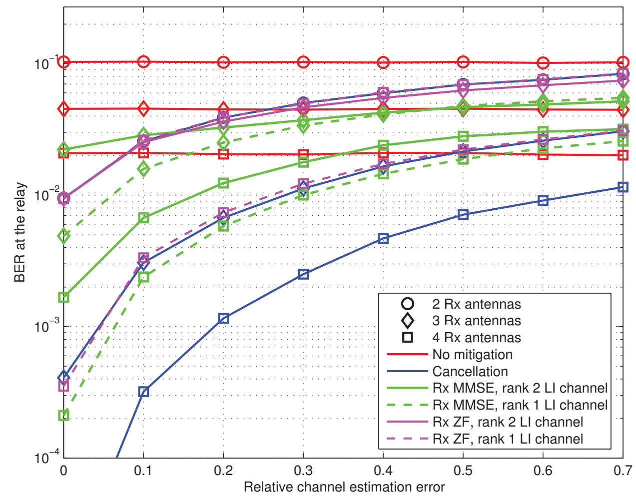

Fig. 6. The effect of channel estimation error in loop interference mitigation. The transmit powers of all compared schemes are normalized to the same value. The signal-to-interference ratio (SNR) of the first hop is 20dB and the signal-to-interference ratio in the relay input is 10dB.

VI. Conclusion

The status quo in relaying literature is to resort to a half-duplex mode and waste spectrum resources by reserving two channel uses for single end-to-end transmission. A full-duplex relaying mode offers large potential which is exploitable after solving the main technical problem, i.e., mitigation of loop interference. We extended the earlier SISO cancellation schemes for the MIMO relay case and proposed alternative schemes that suppress the interference in the spatial domain: null space projection and minimum mean square error (MMSE) filtering. We also discussed the issues that need to be considered when combining time-domain cancellation and spatial suppression. Finally, our simulations illustrated that all proposed schemes offer significant interference mitigation. The estimation error of the loop channel was identified as the main limitation to prevent perfect interference nulling.

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