Optimized Full-Duplex MIMO Relay in SISO Link

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Abstract

A multiple-input multiple-output (MIMO) relay system operating in a full-duplex manner on a single frequency band suffers from self-interference. This paper aims to optimize such a system in single-input single-output (SISO) end-to-end link. It presents numerical signal-to-interference-plus-noise ratio (SINR) performance results of transmit power control and self-interference suppression in spatial domain via beamforming filters.

1 Introduction

The use of relays in wireless communication systems brings some benefits, e.g., higher power efficiency and coverage extension. If the relay operates in the half-duplex mode, two time slots are needed for symbol transmission; one time slot for the source–relay transmission, and another for the relay–destination transmission. Alternatively, frequency-division approach can be adopted to orthogonalize the source–relay and relay–destination links. For either case, the end-to-end capacity is halved due to rate loss. On the contrary, deploying a full-duplex relay does not cause any rate loss in capacity because of spectral reuse. Yet, the simultaneous reception and transmission at the relay generates an interference signal. The system performance can be improved if this self-interference signal is mitigated via, e.g., physical isolation, time-domain cancellation or spatial-domain suppression [1]. In this paper, we investigate the SINR limits of such systems with beamforming and power allocation.

2 System Model

We consider a two-hop communication system with a full-duplex relay, R, between a source, S, and a destination, D, node. The endpoints, S and D, are single-antenna nodes while the relay, R, has N_{rx} receiver and N_{tx} transmitter antennas with the receiver beamforming filter, $\mathbf{g}_{\mathrm{rx}} \in \mathbb{C}^{1\times N_{\mathrm{rx}}}$, and the transmitter beamforming filter, $\mathbf{g}_{\mathrm{tx}} \in \mathbb{C}^{N_{\mathrm{tx}}\times 1}$. The illustration of this model is given in Fig. 1.

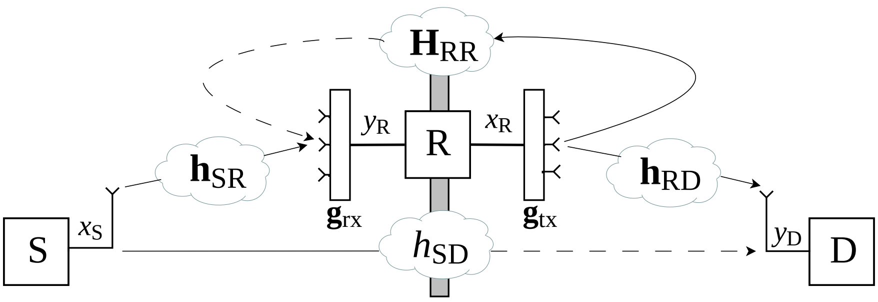

Fig. 1: System model of a two-hop communication system with a full-duplex MIMO relay

The signal, x_S, is transmitted from S and received at both R and D nodes through source–relay, $\mathbf{h}_{SR} \in \mathbb{C}^{N_{rx}\times 1}$, and direct transmission, $h_{SD} \in \mathbb{C}$, channels, respectively. The signal, x_R, is transmitted from R and received at both D and R nodes through relay–destination, $\mathbf{h}_{RD} \in \mathbb{C}^{1\times N_{tx}}$, and relay self-interference, $\mathbf{H}_{RR} \in \mathbb{C}^{N_{rx}\times N_{tx}}$, channels, respectively. The received signals at R node, y_R, and at D node, y_D, are

$$y_R = \mathbf{g}_{rx}\mathbf{h}_{SR}x_S + \mathbf{g}_{rx}\mathbf{H}_{RR}\mathbf{g}_{tx}x_R + \mathbf{g}_{rx}\mathbf{n}_R \quad (1)$$

$$y_D = \mathbf{h}_{RD}\mathbf{g}_{tx}x_R + h_{SD}x_S + n_D \quad (2)$$

We assume the direct link channel, h_{SD}, is too weak to be included in the calculations due to severe path loss, i.e., $h_{SD} \approx 0$. This is reasonable since a relay is not needed in the converse case.

Using (1) and (2), we can write the first-hop SINR, γ_R, and the second-hop SINR, γ_D, as

$$\gamma_R = \frac{|\mathbf{g}_{rx}\mathbf{h}_{SR}|^2 p_S}{|\mathbf{g}_{rx}\mathbf{H}_{RR}\mathbf{g}_{tx}|^2 p_R + \sigma_R^2} \quad (3)$$

$$\gamma_D = \frac{|\mathbf{h}_{RD}\mathbf{g}_{tx}|^2 p_R}{\sigma_D^2} \quad (4)$$

where the transmit signal powers are $p_S = \mathrm{E}\{|x_S|^2\}$ and $p_R = \mathrm{E}\{|x_R|^2\}$, and the additive noise powers are $\sigma_R^2 = \mathrm{E}\{|\mathbf{g}_{rx}\mathbf{n}_R|^2\}$ and $\sigma_D^2 = \mathrm{E}\{|n_D|^2\}$.

The end-to-end system SINR depends on the relay protocol. We study the SINR expressions for amplify-and-forward (AF) and decode-and-forward (DF) protocols.

1. With AF protocol, the relay amplifies the received signal, y_R, in every time slot, k, to obtain the relay transmitted signal, x_R, i.e., $x_R[k] = \beta\ y_R[k - k_d^{AF}]$, where β is the gain factor and k_d^{AF} is the processing delay. The gain factor, β, normalizes the relay transmit power to p_R. Therefore, β^2 is the power ratio between the relay output signal and the relay input signal. By combining (1) and (2), we find the end-to-end SINR for AF protocol as [2]

$$\gamma_{e2e}^{AF} = \frac{\gamma_R\gamma_D}{\gamma_R + \gamma_D + 1} \quad (5)$$

2. With DF protocol, the received signal at the destination node, D, depends upon the particular coding and modulation choices. It is not meaningful to try to define the real end-to-end SINR due to nonlinear decoding/re-encoding processes at the relay. Instead, we define the *effective* end-to-end SINR for DF protocol as [2]

$$\gamma_{e2e}^{DF} = \min\{\gamma_R, \gamma_D\} \quad (6)$$

3 System Optimization

Let us next transform the system model to a nonlinear optimization problem. The functions to be maximized are the SINR expressions, while the optimization parameters are the beamforming vectors and the transmit powers. Based on the choice of constraint functions, we define two optimization problems: global optimization and null-space projection.

1. The global problem is stated as maximizing the end-to-end SINR expressions in (5) and (6), while staying within the transmit power budgets, and keeping the unit beamforming vector norm constraints with the design parameters $\mathbf{g}_{rx}$, $\mathbf{g}_{tx}$, p_S, and p_R. So, it is defined as

$$\text{maximizing } \gamma_{e2e}^{AF} \text{ or } \gamma_{e2e}^{DF} \text{ with the constraints} \quad \begin{cases} 0 \le p_S \le 1 \\ 0 \le p_R \le 1 \\ \|\mathbf{g}_{rx}\|_2 = 1 \\ \|\mathbf{g}_{tx}\|_2 = 1 \end{cases}$$

   By investigating (1) and (2), one can see that the optimal source power, p_S^*, is always 1.

2. The null-space projection optimization problem is defined by introducing an additional constraint to the global optimization, which liberates the system from self-interference. In particular, the null-space projection aims for the maximization of the end-to-end SINR expressions by choosing the beamforming filters among the ones that cancel out the self-interference [1]. So, it is defined as [3, 4]

$$\text{maximizing } \gamma_{\text{e2e}}^{\text{AF}} \text{ or } \gamma_{\text{e2e}}^{\text{DF}} \text{ with the constraints } \begin{cases} 0 \leq p_{\text{R}} \leq 1 \\ \|\mathbf{g}_{\text{rx}}\|_2 = 1 \\ \|\mathbf{g}_{\text{tx}}\|_2 = 1 \\ \mathbf{g}_{\text{rx}} \mathbf{H}_{\text{RR}} \mathbf{g}_{\text{tx}} = 0 \end{cases}$$

   Since the system is now free from interference, the interplay between maximizing γ_{R} and γ_{D} by choosing a particular relay transmit power, p_{R}, no longer exists. Hence, the optimal relay transmit power, p_{R}^*, becomes 1.

The optimization problems formulated above are difficult to solve analytically. However, they can still be tackled by introducing some subconstraints, which would lead us to suboptimal, yet analytical solutions [5]. A logical choice could be to eliminate one of the beamforming filters from being an unknown. If either of the beamforming filters is defined as the matched filter solution to its corresponding channel response, i.e., $\mathbf{g}_{\text{rx}} = \mathbf{h}_{\text{SR}}^{\text{H}} / \|\mathbf{h}_{\text{SR}}\|_2$ or $\mathbf{g}_{\text{tx}} = \mathbf{h}_{\text{RD}}^{\text{H}} / \|\mathbf{h}_{\text{RD}}\|_2$, the other beamforming filter, as well as the relay transmit power, could be optimized. Alternatively, both of the beamforming filters could be defined as the matched filter solutions. Then, the relay transmit power, p_{R}, alone could be optimized [2].

4 Numerical Analysis

Numerical analysis is conducted next for the cases regarding the unconstrained global problem and the null-space projection problem as well as the global problem with matched filter subsolutions for both AF and DF protocols. The results are obtained via Monte Carlo simulations using the nonlinear optimization toolbox of MATLAB®. The system setup can be described as follows. The receiver and transmitter antennas of the relay are varied from one to five, while always being kept equal to each other. Source–relay, $\mathbf{h}_{\text{SR}}$, relay–destination, $\mathbf{h}_{\text{RD}}$, and self-interference, $\mathbf{H}_{\text{RR}}$, channels are assumed to experience Rayleigh fading with independent identically distributed elements. The noise variances at the relay, σ_{R}^2, and at the destination, σ_{D}^2, are normalized to one. The average power gain per each subchannel for the source–relay and relay–destination links are set to be 15 dB, whereas for the self-interference subchannels, it is set to be 5 dB.

Five different cases are considered for AF and DF protocols each: 1) The global problem is taken as it is. The beamforming vectors, $\mathbf{g}_{\text{rx}}$ and $\mathbf{g}_{\text{tx}}$, and the relay transmit power, p_{R}, are assumed to be the optimization parameters. 2) The null-space projection constraint is introduced to the global problem. The optimal set of beamforming vectors, $\mathbf{g}_{\text{rx}}$ and $\mathbf{g}_{\text{tx}}$, that satisfy the constraint are investigated provided optimal maximum relay transmit power, $p_{\text{R}}^* = 1$. 3) Receiver beamforming filter, $\mathbf{g}_{\text{rx}}$, is assumed to be matched to the source–relay channel, $\mathbf{h}_{\text{SR}}$, while transmitter beamforming vector, $\mathbf{g}_{\text{tx}}$, and the relay transmit power, p_{R}, are taken as the optimization parameters. 4) Transmitter beamforming vector, $\mathbf{g}_{\text{tx}}$, is assumed to be matched to the relay–destination channel, $\mathbf{h}_{\text{RD}}$, while the receiver beamforming vector, $\mathbf{g}_{\text{rx}}$, and the relay transmit power, p_{R}, are taken as the optimization parameters. 5) Both the receiver beamforming vector, $\mathbf{g}_{\text{rx}}$, and the transmitter beamforming vector, $\mathbf{g}_{\text{tx}}$, are assumed to be matched to the respective source–relay, $\mathbf{h}_{\text{SR}}$, and relay–destination, $\mathbf{h}_{\text{RD}}$, channels, while the relay transmit power, p_{R}, is taken as the only optimization parameter. For each case above, the evaluation is run over a sufficient number of channel realizations, and the resulting SINR values are averaged over them.

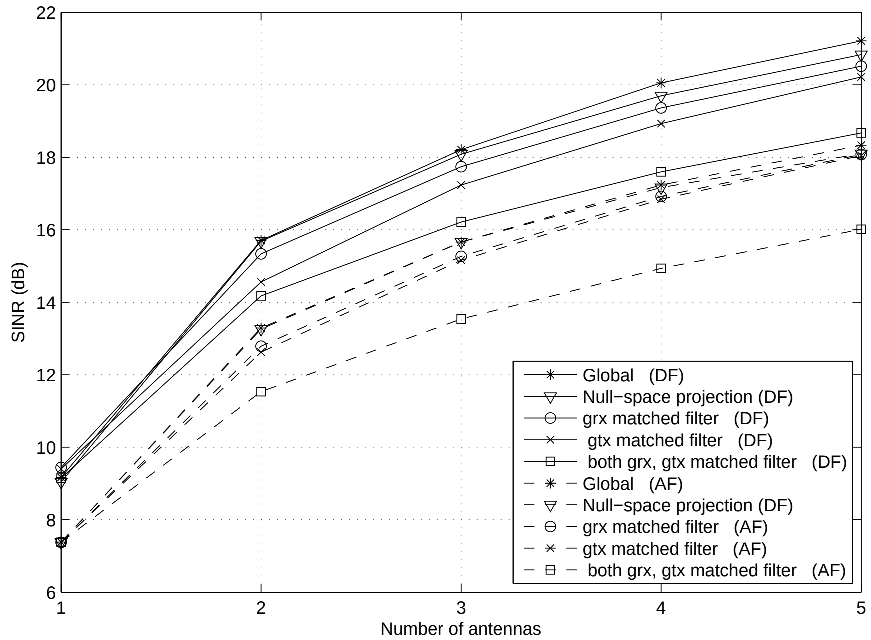

Fig. 2: Numerical evaluation results for global optimization and null-space projection

Fig. 2 shows the simulation results with the end-to-end SINR values on the vertical axis versus the number of relay antennas along the horizontal axis. Firstly, we see that as the number of antennas increases, SINR performance for each case improves. However, the additional SINR gain for each extra antenna decreases as the number of antennas increases. Global solution gives the highest SINR values, which are the theoretical upper limits. The null-space projection solution results in almost identical SINR performance. The case in which the receiver beamforming vector, $\mathbf{g}_{rx}$, is matched and the case in which the transmitter beamforming vector, $\mathbf{g}_{tx}$, is matched produce only slightly lower SINR performance, whereas the case which sets both of the beamforming vectors, $\mathbf{g}_{rx}$ and $\mathbf{g}_{tx}$, as matched filters results in much lower SINR values. Thereby, setting only one of the beamforming vectors as matched filter does not cause much SINR loss in practice, especially as compared to the case in which both of the beamforming vectors are set to be matched filters.

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