Pareto Boundary for Massive-MIMO-Relay-Assisted Interference Networks: Half-duplex vs. Full-duplex Processing

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***Abstract*—Due to the absence or insufficient strength of the direct links between communication pairs, relay-assisted communication is inevitable in communication networks. One important class of such networks is the interference relay channel, whose Pareto boundary of the achievable rate region is investigated in this paper. The relay is equipped with multiple antennas for transmission and reception while the source and destination nodes have a single antenna each. Due to relatively high strength of the relay links compared to the direct links, the destinations decode the relay signals while the other receiving signals from the sources through direct links are treated as noise (TIN). We consider both zero-forcing (ZF) and maximum ratio transmission/combining (MRT/MRC) at the relay input and output, while the relay can either operate in half-duplex or full-duplex mode. The power is optimized in order to characterize the Pareto boundary considering these two types of beamforming strategies. We formulate the weighed max-min optimization problem which delivers the Pareto boundary. This problem turns out to be a geometric program (GP) which can be converted to a convex optimization problem and solved efficiently. We observe that, by increasing the number of transmit and receive antennas at the relay significantly, full-duplex outperforms half-duplex even at strong self-interference channels.**

I. Introduction

Relay-assisted communication has been shown to be beneficial from different perspectives. For instance, when the direct links between the users are weak or missing, relaying the source signal becomes the only option. Hence, studying efficient relaying techniques is of crucial importance. A relay can amplify the received signal from the sources and forward it to the destinations without resorting signal processing tasks [1]. Alternatively, more efficient relaying strategies such as decode-and-forward, compress-and-forward, and compute-and-forward can be applied by involving digital signal processing at the relay [2], [3]. The optimal relaying strategy of the single-input single-output (SISO) interference relay channel has been investigated in [4], [5] from the generalized degrees-of-freedom (GDoF) viewpoint. Note that, GDoF is an approximation of the capacity at high SNR.

Utilizing full-duplex operation at the relay is an outstanding approach to enhance the achievable rates, as full-duplex operation is able to almost double [6]. Technically, LI could be considered as the most significant hurdle for full-duplex communication [7]. This is due to transmission and reception at the same channel use (time instant or frequency bin) which induces an excess interference on signal reception. Multiple techniques might be employed for coping with this interference. One way could be to passively cancel LI by proper physical isolation of transmission and reception [6], [8]. Active LI cancellation can also be considered at either analog or digital domains, however a hybrid cancellation could be an option as well [9], [10]. An alternative approach for LI cancellation is the usage of large antenna array (massive MIMO) at the full-duplex node. Recently, massive MIMO has been explored for improving the system performance in wireless communication networks. The authors in [11] studied massive MIMO for improving the beam directivity by improving the signal-to-interference-plus-noise ratio (SINR), although the degrees-of-freedom (DoF) or capacity prelog can be enhanced by serving large number of users simultaneously interference-free. By deploying large antenna array for transmission at the relay, narrower beams can be directed to destination by maximum-ratio transmission (MRT) beamforming which improves the signal to noise ratio (SNR) for each user. Alternatively, zero-forcing (ZF) beamforming can null the interference at the destinations which is optimal at high interference regimes. The authors in [12] study the performance of full-duplex massive MIMO decode-and-forward relay from the power perspective while using ZF and MRT/MRC at the relay. Furthermore, the authors in [13] study the spectral efficiency of massive MIMO full-duplex amplify-and-forward relay in the presence of inter-user interference (IUI).

In this paper, we consider decode-and-forward full-duplex MIMO relaying with inter-user interference. This type of interference is not negligible if the source of at least one communicating pair is in the vicinity of the destination of at least one other communicating pair. By utilizing ZF and MRC/MRT at the relay input/output, we formulate the weighted max-min optimization problem in order to capture the outer-most boundary of the rate region. Defining an auxiliary optimization parameter, the problem turns out to be a geometric program (GP) which can be solved efficiently. Considering optimal power allocation, we show the superiority of ZF over MRC/MRT from the achievable rate region perspective, given less antennas at the relay. By increasing the number of antennas at the relay, this gap tends to collapse. Furthermore, we highlight the performance gap of full-duplex relaying with LI compared with half-duplex relaying as a function of

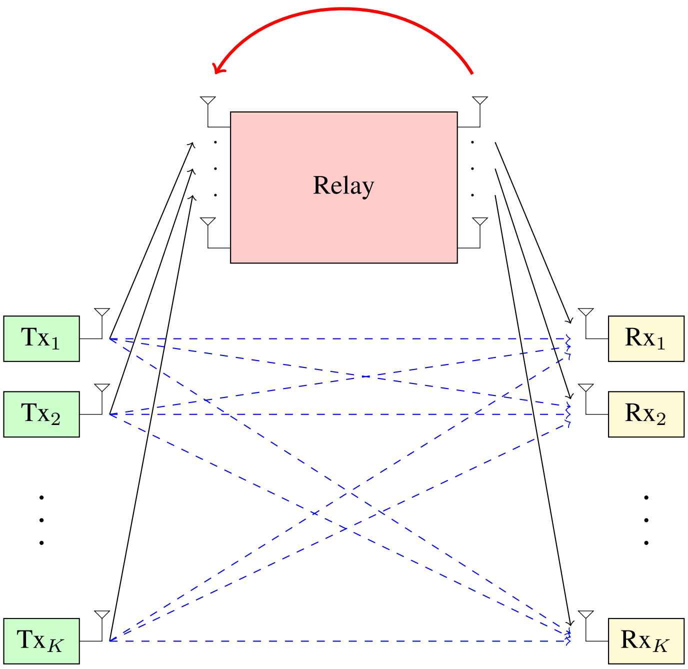


Fig. 1: Relay interference channel with full-duplex operation. The relay is equipped with multiple transmit and receive antennas while the source and destination nodes have a single antenna. Inter-user interference is shown by dashed lines, while the loop interference channel is shown in red.

transmit/receive antenna quantity.

II. System Model

We consider a MIMO relay equipped with N_t transmit and N_r receive antennas. This relay connects K sources with their corresponding destinations as shown in Fig. 1 by using decode-and-forward strategy. The channel input-output relationship between the kth source and the relay and between the relay and kth destination is given as

$$\mathbf{y}_r = \sum_{k=1}^{K} \mathbf{h}_{\mathrm{rs}_k} x_k + \mathbf{H}_{\mathrm{rr}} \mathbf{x}_{\mathrm{r}} + \mathbf{n}_{\mathrm{r}}, \tag{1}$$

$$y_k = \mathbf{h}_{\mathrm{d}_k\mathrm{r}}^H \mathbf{x}_{\mathrm{r}} + \sum_{l=1}^{K} h_{\mathrm{d}_k\mathrm{s}_l} x_l + n_{\mathrm{d}_k} \tag{2}$$

where $\mathbf{h}_{\mathrm{rs}_k}$, $\mathbf{h}_{\mathrm{d}_k\mathrm{r}}$, $\mathbf{H}_{\mathrm{rr}}$ and $h_{\mathrm{d}_k\mathrm{s}_j}$ are the source-relay, relay-destination, loop interference and source-destination channels, respectively. In this paper, we assume that the channels $\mathbf{h}_{\mathrm{rs}_k}$ and $\mathbf{h}_{\mathrm{d}_k\mathrm{r}}$ are perfectly known at the relay. The noise realizations at the relay and at the kth destination are represented by $\mathbf{n}_{\mathrm{r}}$ and n_{d_k}, respectively.

The signal x_k is the transmit signal from the kth source and $\mathbf{x}_r$ is the precoded transmit signal from the relay given by

$$\mathbf{x}_{\mathrm{r}} = \sum_{k=1}^{K} \mathbf{w}_k d_k = \mathbf{W}\mathbf{d}, \tag{3}$$

$$\tag{4}$$

where the information symbol d_k intended for the kth destination is linearly beamformed in the direction of $\mathbf{w}_k$. Note that $\mathbf{W} = [\mathbf{w}_1 ... \mathbf{w}_K]$ and $\mathbf{d} = [d_1 ... d_K]^T$. We assume that the vector of transmit information symbols $\mathbf{d}$ at the relay has identical independent Gaussian distributed elements. Therefore, it has a diagonal covariance matrix $\mathbf{C}$. Notice that the diagonal elements of $\mathbf{C}$ indicate the allocated power for the corresponding information symbols, i.e., $\mathbf{C}_{kk} = p_{\mathrm{r}_k}$. Thereby, the transmit beamformed signal at the relay fulfils the following constraint,

$$\mathbb{E}[\mathbf{x}_r^H \mathbf{x}_r] = \sum_{k}^{K} p_{\mathrm{r}_k} ||\mathbf{w}_k||^2 \leq P_{\mathrm{r}}, \tag{5}$$

$$||\mathbf{w}_k||^2 = 1, \ \forall k \tag{6}$$

where P_{r} is the transmit power budget at the relay. Moreover, the beamforming vectors are normalized to unit-norm. The beamforming strategy at the relay station is assumed to be either zero-forcing (ZF) or maximum-ratio transmission (MRT). Zero-forcing beamforming at the relay, forces the signals from the undesired information symbols to zero at all destinations if enough degrees-of-freedom are available which is achieved when $N_t \geq K$. As an alternative, maximum-ratio transmission towards destination k forms the desired information symbol in the direction of the desired channel of destination k, such that the signal-to-noise ratio (SNR) is maximized. Mathematically,

$$\mathbf{w}_k^{(\mathrm{zf})} \in \ \mathrm{Null}\{\mathbf{h}_{\mathrm{d}_1\mathrm{r}} ... \mathbf{h}_{\mathrm{d}_{k-1}\mathrm{r}} \mathbf{h}_{\mathrm{d}_{k+1}\mathrm{r}} ... \mathbf{h}_{\mathrm{d}_K\mathrm{r}}\}, \tag{7}$$

$$\mathbf{w}_k^{(\mathrm{mrc})} = \frac{\mathbf{h}_{\mathrm{d}_k\mathrm{r}}}{||\mathbf{h}_{\mathrm{d}_k\mathrm{r}}||}. \tag{8}$$

The received signal at the relay is linearly post-coded using parallel filters $\mathbf{u}_k^H$, $\forall k \in \{1, ..., K\}$, in order to get the desired signal as

$$\tilde{y}_{\mathrm{r}_k} = \mathbf{u}_k^H \mathbf{y}_{\mathrm{r}}, \tag{9}$$

where $\mathbf{u}_k$ is the receive beamforming vector specified for user k. Here, we assume the receive beamforming vectors to be either ZF or maximum-ratio combining (MRC). Hence,

$$\mathbf{u}_k^{(\mathrm{zf})} \in \ \mathrm{Null}\{\mathbf{h}_{\mathrm{rs}_1} ... \mathbf{h}_{\mathrm{rs}_{k-1}} \mathbf{h}_{\mathrm{rs}_{k+1}} ... \mathbf{h}_{\mathrm{rs}_K}\}, \tag{10}$$

$$\mathbf{u}_k^{(\mathrm{mrc})} = \mathbf{h}_{\mathrm{rs}_k}. \tag{11}$$

Notice that the normalization of receive beamforming, does not effect the SINR. The null-spaces in (7) and (10) have multiple eigen-vectors depending on the difference between the number of antennas at the relay and the number of users. Hence, multiple directions in the null-space can zero-force the unintended signals at the relay in the precoding and postcoding phases. Thereby, SINR-optimal ZF directions (at the transmitter and receiver sides of the relay) can be analytically formulated to be the columns of the following matrices, [12].

$$\mathbf{W}^{(\mathrm{zf})} = \mathbf{H}_{\mathrm{dr}} (\mathbf{H}_{\mathrm{dr}}^H \mathbf{H}_{\mathrm{dr}})^{-1}, \tag{12}$$

$$\mathbf{U}^{(\mathrm{zf})} = \mathbf{H}_{\mathrm{rs}} (\mathbf{H}_{\mathrm{rs}}^H \mathbf{H}_{\mathrm{rs}})^{-1}, \tag{13}$$

where ZF matrices at the transmitter and receiver of the relay are represented by $\mathbf{W}^{(\mathrm{zf})}$ and $\mathbf{U}^{(\mathrm{zf})}$, respectively. Note that, $\mathbf{H}_{\mathrm{dr}} = [\mathbf{h}_{\mathrm{d}_1\mathrm{r}} ... \mathbf{h}_{\mathrm{d}_K\mathrm{r}}]$ and $\mathbf{H}_{\mathrm{rs}} = [\mathbf{h}_{\mathrm{rs}_1} ... \mathbf{h}_{\mathrm{rs}_K}]$. Furthermore, the columns of the beamforming matrix $\mathbf{W}^{(\mathrm{zf})}$ need to fulfil unit-norm constraint in order to be consistent with (6). In the next section we formulate the optimization problem that characterizes the outer-most boundary of the rate region.

III. Rate Region

The achievable rate of the message from source k to its corresponding destination is limited by the minimum of the achievable rates given by the source-relay and relay-destination links. That means

$$R_k = \min\{R_{\mathrm{s}_k\mathrm{r}}, R_{\mathrm{rd}_k}\}. \quad (14)$$

By treating interference as noise (TIN) at the relay and destination nodes, the achievable rates of the source-relay and the relay-destination links are formulated at the top of next page by (15) and (16), where the corresponding SINR expressions are represented by $S_{\mathrm{s}_k\mathrm{r}}$ and S_{rd_k}, respectively. Hence, the achievable rates are functions of transmitted power of the sources and the relay given the beamforming vectors at the relay. For simplicity in representation we define,

$$\mathbf{p}_{\mathrm{s}} = [p_1, ..., p_K], \quad (17)$$
$$\mathbf{p}_{\mathrm{r}} = [p_{\mathrm{r}_1}, ..., p_{\mathrm{r}_K}]. \quad (18)$$

In order to characterize the achievable rate region, we need to formulate an appropriate optimization problem that captures the outer-most boundary which is called the Pareto boundary of the rate region. All the rate tuples on this boundary are of interesting property, so that an increment in the rate of one user can not coincide with an increment in the rate of any of the other users. Some particular points on the Pareto boundary can be utilized as the operating points of the system since they are optimal. Several formulation of optimization problems can manifest the Pareto boundary, though many of them end up in a non-convex problem. We utilize the weighted max-min optimization problem [14], which is formulated as,

$$\begin{aligned} \max_{\mathbf{p}_{\mathrm{s}},\mathbf{p}_{\mathrm{r}}} \quad & \min\ \mathcal{S} && (19)\\ \text{s.t.} \quad & p_k \leq P_k, \quad \forall k \in \{1, ..., K\}, && (19a)\\ & \sum_{k=1}^{K} p_{\mathrm{r}_k} \leq P_{\mathrm{r}},, && (19b) \end{aligned}$$

where P_k and P_{r} are the transmit power constraints at the kth source and at the relay, respectively. Moreover, $\mathcal{S}$ is the set of the weighted achievable SINRs between the sources and the destinations. Note that the achievable rates are functions of achievable SINRs as shown in (15) and (16). Hence,

$$\mathcal{S} = \left\{ \frac{1}{\alpha_1} \min\{S_{\mathrm{s}_1\mathrm{r}}, S_{\mathrm{rd}_1}\}, ..., \frac{1}{\alpha_K} \min\{S_{\mathrm{s}_K\mathrm{r}}, S_{\mathrm{rd}_K}\} \right\} \quad (20)$$

where $\sum_{k=1}^{K} \alpha_k = 1$. Note that, $\boldsymbol{\alpha} = [\alpha_1, ..., \alpha_K]$ is the vector of SINR weights, where

$$\boldsymbol{\alpha} \in \mathcal{A} = \{\boldsymbol{\alpha} | \sum_{k=1}^{K} \alpha_k = 1\}. \quad (21)$$

Hence, by considering all $\boldsymbol{\alpha} \in \mathcal{A}$ we can characterize the Pareto boundary of the rate region by acquiring the optimal power for the sources and the relay according to problem (19). We define an auxiliary variable $\Gamma = \min\ \mathcal{S}$. Then, problem (19) can be reformulated as

$$\begin{aligned} \max_{\mathbf{p}_s,\mathbf{p}_{\mathrm{r}},\Gamma} \quad & \Gamma && (22)\\ \text{s.t.} \quad & \alpha_k \Gamma \leq S_{\mathrm{s}_k\mathrm{r}}, \quad \forall k \in \{1, ..., K\} && (22a)\\ & \alpha_k \Gamma \leq S_{\mathrm{rd}_k}, \quad \forall k \in \{1, ..., K\} && (22b)\\ & p_k \leq P_k, \quad \forall k \in \{1, ..., K\}, && (22c)\\ & \sum_{k=1}^{K} p_{\mathrm{r}_k} \leq P_{\mathrm{r}}, && (22d) \end{aligned}$$

Then, problem (22) can be reformulated as

$$\begin{aligned} \max_{\mathbf{p}_{\mathrm{s}},\mathbf{p}_{\mathrm{r}},\Gamma} \quad & \Gamma && (23)\\ \text{s.t.} \quad & \alpha_k \Gamma S_{\mathrm{s}_k\mathrm{r}}^{-1} \leq 1, \quad \forall k \in \{1, ..., K\} && (23a)\\ & \alpha_k \Gamma S_{\mathrm{rd}_k}^{-1} \leq 1, \quad \forall k \in \{1, ..., K\} && (23b)\\ & p_k \leq P_k, \quad \forall k \in \{1, ..., K\}, && (23c)\\ & \sum_{k=1}^{K} p_{\mathrm{r}_k} \leq P_{\mathrm{r}}, && (23d) \end{aligned}$$

Optimization problem (23) is a geometric program (GP), where the objective and the constraints are posynomials. This problem can be reformulated to a convex problem and solved efficiently [15]. Algorithm 1 explains the procedure briefly.

Algorithm 1 Pareto boundary characterization

1: Specify the weights, $\forall \boldsymbol{\alpha} \in \mathcal{A}$
2: Solve the geometric program stated in (23).
3: Acquire optimal power solutions, i.e., $\mathbf{p}_s$, $\mathbf{p}_{\mathrm{r}}$
4: Calculate the achievable rates from (14)-(16).

As a comparison benchmark, we study the achievable rate region of half-duplex relay as well. According to the fact that, in the half-duplex setup the sources and the relay transmit in orthogonal dimensions (i.e., time, frequency), hence no loop interference and inter-user interference occur. This results in improving the signal-plus-interference-and-noise-ratio (SINR) at the expense of a reduction in degrees-of-freedom (DoF). In order to have a fair comparison between the achievable rate regions of full-duplex and half-duplex relays, we need to double the power consumption in half-duplex relay problem compared to full-duplex relay problem. Here, doubling the transmit power for all sources and the relay coincides with the same achievable rates as by halving the noise power. Hence, the achievable rates by considering relay with half-duplex operation can be formulated as

$$R_{\mathrm{s}_k\mathrm{r}}^{HD} = \frac{1}{2} \log \left(1 + \frac{p_k |\mathbf{u}_k^H \mathbf{h}_{\mathrm{rs}_k}|^2}{\sum_{\substack{l=1\\ l\neq k}}^{K} p_l |\mathbf{u}_k^H \mathbf{h}_{\mathrm{rs}_l}|^2 + \frac{\sigma^2}{2} ||\mathbf{u}_k||^2} \right), \quad (24)$$

$$R_{\mathrm{rd}_k}^{HD} = \frac{1}{2} \log \left(1 + \frac{p_{\mathrm{r}_k} |\mathbf{h}_{\mathrm{d}_k\mathrm{r}}^H \mathbf{w}_k|^2}{\sum_{\substack{j=1\\ j\neq k}}^{K} p_{\mathrm{r}_j} |\mathbf{h}_{\mathrm{d}_j\mathrm{r}}^H \mathbf{w}_j|^2 + \frac{\sigma^2}{2}} \right). \quad (25)$$

For the characterization of the rate region of a half-duplex relaying system, we can proceed with a similar optimization

$$R_{\mathrm{s}_k\mathrm{r}}^{FD} = \log\left(1 + \frac{\overbrace{p_k|\mathbf{u}_k^H\mathbf{h}_{\mathrm{rs}_k}|^2}^{S_{\mathrm{s}_k\mathrm{r}}}}{\sum_{\substack{l=1\\l\neq k}}^{K} p_l|\mathbf{u}_k^H\mathbf{h}_{\mathrm{rs}_l}|^2 + \underbrace{\sum_{j=1}^{K} p_{\mathrm{r}_j}||\mathbf{u}_k^H\mathbf{H}_{\mathrm{rr}}\mathbf{w}_j||^2}_{\text{self-interference}} + \sigma^2||\mathbf{u}_k||^2}\right) \quad (15)$$

$$R_{\mathrm{rd}_k}^{FD} = \log\left(1 + \frac{\overbrace{p_{\mathrm{r}_k}|\mathbf{h}_{\mathrm{d}_k\mathrm{r}}^H\mathbf{w}_k|^2}^{S_{\mathrm{rd}_k}}}{\sum_{\substack{j=1\\j\neq k}}^{K} p_{\mathrm{r}_j}|\mathbf{h}_{\mathrm{d}_j\mathrm{r}}^H\mathbf{w}_j|^2 + \underbrace{\sum_{l=1}^{K} p_l|\mathbf{h}_{\mathrm{d}_k\mathrm{s}_l}^H|^2}_{\text{inter-user interference}} + \sigma^2}\right) \quad (16)$$

framework as in algorithm 1.
In the next section we proceed with the numerical results on the characterization of the rate region in half-duplex and full-duplex relaying systems with both ZF and MRT/MRC relay.

IV. Numerical Results

In this section we present the simulation results which is mainly according to algorithm 1. We analyse the rate region of the following systems.

A. Authorized system: two authorized sources communicating with their corresponding destinations. Here, we determine the achievable rate region.
B. Unauthorized system: multiple authorized sources communicating with multiple destinations, while two unauthorized pairs are trying to access the channel simultaneously. Here, we determine the unauthorized users' rate region under authorized systems SINR constraints. Note that, each SINR constraint is a posynomial constraint.

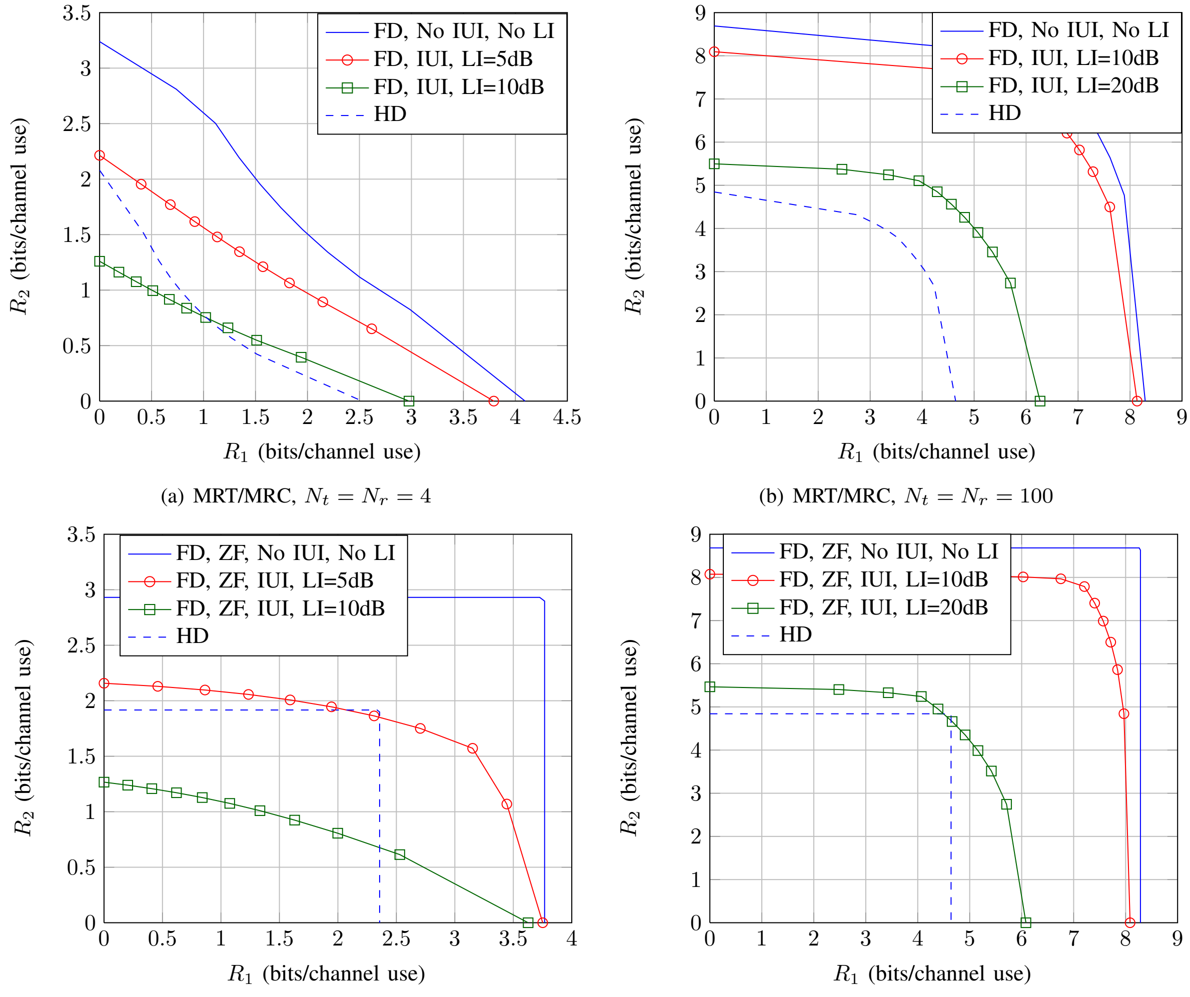
In the next sections we study the numerical results for these two cases elaborately. In our simulations we assumed receiver noise variance σ^2 equal to 1. Moreover, the maximum available power at the sources and at the relay are limited to 2 and 10 units, respectively.

A. Authorized System

Here, we provide the achievable rate region of the two-pair relay communication, where the communication between both pairs are held through multiple-antenna relay. The rate region of the full-duplex and half-duplex relay is compared at various LI strengths. The upper-bound of the achievable rate region can be expressed in the case when the loop interference is perfectly cancelled, however not possible practically, and the direct links between the users do not exist at all. This case is considered as the optimality benchmark for the utilized schemes. Furthermore, we compare the performance of ZF and MRT/MRC beamforming at the relay from the highest achievable rate perspective. According to Fig. 2(a) which corresponds to MRT/MRC at the relay with 4 transmit and 4 receive antennas, i.e., $N_t = N_r = 4$, the rate region delivered by full-duplex dominates the rate region of half-duplex at low-enough LI, e.g., $LI \leq 5dB$. As the interference channel strength increases, the achievable rates of full-duplex relay becomes worse than the one with half-duplex relay. Notice that, ZF achieves higher rate-tuples compared to MRT/MRC, since the simulation parameters turn the system to be interference-limited for which ZF outperforms MRT/MRC.
By increasing the number of transmit and receive antennas at the relay significantly and considering MRT/MRC at the relay, full-duplex operation dominates the half-duplex even at very high LI ranges. As depicted in Fig. 2(b), having very strong LI, full-duplex achievable rates are significantly higher than the ones with half-duplex. Besides, the detrimental effect of IUI can be alleviated as the number of relay antennas increase. Notice that, ZF achieves better rate-tuples, but as the strength of the LI increases, the achievable rates decrease drastically. This is due to an excess interference projected on the sub-space spanned by the desired signal at the relay. Notice that, for both cases i.e., 4 antenna and 100 antenna at the relay, enough degrees-of-freedom is available for projecting loop interference on the null-space of the desired signal if the loop interference channel is given. However, it is not the case in this paper.

B. Unauthorized System

In this section we involve several pairs in the scenario, namely 10 users demand to access the channel simultaneously, meanwhile requiring the relay for the communications. We assume 8 users are authorized users with QoS demands (SINR demands). The remaining 2 unauthorized users can only access the channel if the QoS demands of the authorized users are fulfilled. Fig. 3 depicts the achievable rate region for the unauthorized system, while satisfying particular SINR demands of the authorized users. As shown in this figure, by having significantly large antenna array at the relay transmission and reception, i.e., $N_t = N_r = 100$, higher demands can be fulfilled, meanwhile higher rates can be achieved by the unauthorized system.



(a) MRT/MRC, $N_t = N_r = 4$

(b) MRT/MRC, $N_t = N_r = 100$

(c) ZF, $N_t = N_r = 4$

(d) ZF, $N_t = N_r = 100$

Fig. 2: Comparison between the achievable rate region of maximum-ratio transmission/maximum-ratio combining (MRT/MRC) and zero-forcing (ZF) at the relay. Besides, the performance of the full-duplex and half-duplex operation is compared.

V. Conclusion

In this paper, we studied the achievable rate region of a relay interference network in which the relay operates either in half-duplex or full-duplex mode. Furthermore, we studied the performance of the relay for small-scale array and massive array from the achievable rate-region perspective. Considering zero-forcing (ZF) and maximum-ratio transmission/reception (MRT/MRC), the weighted max-min optimization problem is formulated. The problem turns out to be a geometric program (GP) which can be solved efficiently in polynomial time. We observed that, by exploiting large array of antennas at the relay the destructive effect of loop interference and inter-user interference can be reduced significantly in full-duplex mode. This can be seen by comparing the achievable rate region of half-duplex with full-duplex processing.

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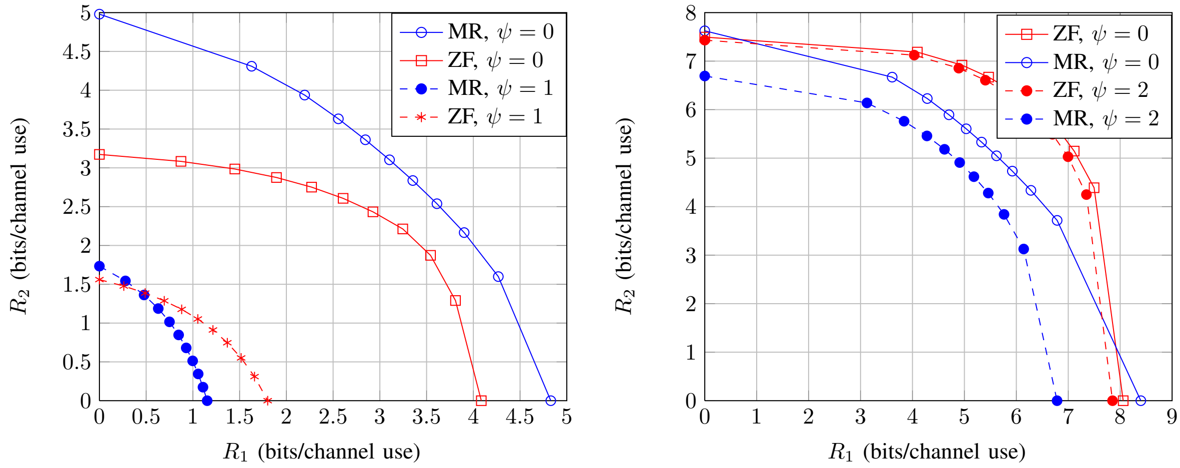

(a) $N_t = N_r = 20$

(b) $N_t = N_r = 100$

Fig. 3: Achievable rate regions of unauthorized users while satisfying the SINR demands of authorized users. Note that, ψ represents the SINR demand which is assumed to be equal for all authorized users. Here, we assume that the full-duplex relay has 10dB leakage. The achievable rate region of zero-forcing (ZF) and maximum-ratio transmission/maximum-ratio combining (MRT/MRC) are compared with different number of relay antenna.

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