# SPECTRUM AND INFRASTRUCTURE SHARING IN THE MIMO INTERFERENCE RELAY CHANNELS

*Jianhui Li, Florian Roemer, and Martin Haardt*

Communications Research Laboratory, Ilmenau University of Technology
P. O. Box 100565, D-98693 Ilmenau, Germany, http://tu-ilmenau.de/crl
Email: {jianhui.li, florian.roemer, martin.haardt}@tu-ilmenau.de

## ABSTRACT

In this paper, single-stream transmission in the MIMO interference relay channel is studied. Two independent transceiver pairs with multiple antennas belonging to different operators communicate with the assistance of one relay, which operates in half-duplex mode and employs an amplify-and-forward strategy. The relay that is shared between the two operators also has multiple antennas. First, the interference relay channel is converted to the conventional interference channel via a preliminarily determined relay amplification matrix. Various relay amplification matrices are investigated for this conversion. Then, the flexible coordinated beamforming for the interference relay channel (IRC FlexCoBF) is proposed for the transceivers. The IRC FlexCoBF algorithm is compared to the alternative schemes proposed in the literature. Simulations show that IRC FlexCoBF achieves a better sum rate performance. Furthermore, a higher robustness to the interferences is demonstrated for IRC FlexCoBF compared to the state of the art. Simulation results show that by sharing a relay between two operators a significant gain in sum rate can be achieved compared to the relay channel.

## 1. INTRODUCTION

In current wireless communication systems, the radio spectrum and the infrastructure are typically used such that interference is avoided by exclusive allocation of frequency bands and employment of base stations. From a communications engineering point of view, different types of orthogonality (frequency, time, code) have been used for resource allocation depending on the type of interference. Very recently, techniques for separating transmissions from different operators (inter-operator interference) without orthogonal resource allocation have been developed. First flexible resource sharing approaches have been designed and results indicate that the overall efficiency of the system can be improved by sharing different resources in the network between several operators [1, 2]. Inspired by this, the seventh European framework project SAPHYRE (sharing physical resources) [3] has been launched which demonstrates how equal-priority resource sharing in wireless networks improves the spectral efficiency, enhances coverage, increases user satisfaction, leads to increased revenue for operators, and decreases capital and operating expenditures.

The physical resources which are shared can be divided into two classes, namely spectrum and infrastructure. These are shared with respect to a set of ‘players’, consisting of operators and users. The interference channel (IC) models two concurrent point-to-point transmissions interfering each other, which is one of the fundamental building blocks from the spectrum sharing point of view. It has been intensely studied over last few decades starting from [4]. Furthermore, it is known since the pioneering work in [5] that relays assisting the communications can significantly improve the end-to-end throughput, outage performance, etc. This has sparkled the interest for finding efficient relaying schemes and exploiting the benefit of the relay sharing. In this paper, we investigate an IC assisted by a relay which we refer to as the interference relay channel (IRC) as depicted in Fig. 1, where the relay is accessed by both transmitters jointly. We show the possible advantages of this scheme compared to an exclusive access via time division multiple access (TDMA). We can view this issue as a special case of voluntary infrastructure and spectrum sharing, which has been investigated in SAPHYRE.

In this work, a single stream transmission of the IRC is studied. It is shown that the IRC can be simplified to the IC as long as the relay precoder is fixed. First, we summarize several relaying algorithms which are adapted to the IRC. After that precoders designed for the IC can be applied at the transceivers. Inspired by the idea from [6], we propose a linear precoding method. The recent work [7] is taken as a benchmark, where a linear coordinated beamformer was designed under zero interference constraints. Simulations demonstrate that the IRC FlexCoBF achieves a better sum rate performance. Furthermore, the robustness to the interferences is investigated for the IRC FlexCoBF as well as previous methods. Finally, it is observed that there is a sum rate gain of the IRC over the traditional relay channel (RC) that consists of a relay in addition to a point-to-point transmission, which strongly shows the advantage of the relay sharing instead of accessing the relay in a TDMA mode. The paper is organized as follows. In Chapter 2, the system model of IRC is introduced. Then various relay amplification matrices are designed in the Subsection 2.1. As soon as the relay amplification matrix is determined, the IRC is converted into the IC and the precoder design at the BS is explained in Subsection 2.2. All the simulation results are presented in Chapter 3 and finally Chapter 4 concludes our work.

## 2. SYSTEM MODEL

The system model is shown in Fig. 1, where two base stations (BSs) belonging to two operators transmit data to their target user terminals (UTs) with the assistance of a shared relay. Throughout this paper, a half-duplex and amplify-and-forward (AF) relay is utilized. The BSs and UTs are equipped with $M_{\mathrm{T},i}$ and $M_{\mathrm{U},i}$ antennas respectively, where $i = 1, 2$ denotes the index of each transceiver pair. The relay has $M_{\mathrm{R}}$ antennas. We assume that a single data stream per UT is transmitted.

The transmission process is divided into two phases.

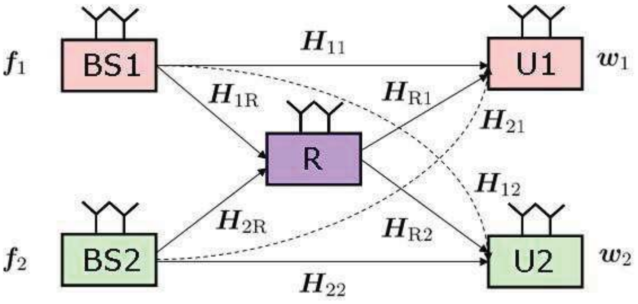

Figure 1: Block Diagram of the Interference Relay Channel where the relay R (infrastructure) and spectrum are shared between the operators 1 and 2

During the first phase, both BSs transmit to their desired UTs and the relay. The received signal at each UT and the relay is

$$\begin{aligned} \boldsymbol{y}_1^{(1)} &= \boldsymbol{H}_{11}\boldsymbol{f}_1 s_1 + \boldsymbol{H}_{21}\boldsymbol{f}_2 s_2 + \boldsymbol{n}_1^{(1)}, \\ \boldsymbol{y}_2^{(1)} &= \boldsymbol{H}_{22}\boldsymbol{f}_2 s_2 + \boldsymbol{H}_{12}\boldsymbol{f}_1 s_1 + \boldsymbol{n}_2^{(1)}, \\ \boldsymbol{y}_{\mathrm{R}} &= \boldsymbol{H}_{1\mathrm{R}}\boldsymbol{f}_1 s_1 + \boldsymbol{H}_{2\mathrm{R}}\boldsymbol{f}_2 s_2 + \boldsymbol{n}_{\mathrm{R}}, \end{aligned}$$

where $\boldsymbol{H}_{ij} \in \mathbb{C}^{M_{\mathrm{U},j} \times M_{\mathrm{T},i}}$, $i, j \in \{1,2,\mathrm{R}\}$ denotes the channel matrices between BSs, UTs, and relay, which are assumed to undergo frequency flat quasi static block fading. The precoder at each BS is $\boldsymbol{f}_i \in \mathbb{C}^{M_{\mathrm{T},i} \times 1}$ and the transmitted data signal is $s_i$. In the second phase, the relay amplifies the received signal from phase 1 and forwards it to the UTs. The signal vectors received at UTs during phase 2 are given by

$$\begin{aligned} \boldsymbol{y}_1^{(2)} =& \boldsymbol{H}_{\mathrm{R}1}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{y}_{\mathrm{R}} + \boldsymbol{n}_1^{(2)}, \\ =& \boldsymbol{H}_{R1}\boldsymbol{F}_R\boldsymbol{H}_{1R}\boldsymbol{f}_1 s_1 + \boldsymbol{H}_{R1}\boldsymbol{F}_R\boldsymbol{H}_{2R}\boldsymbol{f}_2 s_2 \\ &+ \boldsymbol{H}_{R1}\boldsymbol{F}_R\boldsymbol{n}_R + \boldsymbol{n}_1^{(2)} \\ \boldsymbol{y}_2^{(2)} =& \boldsymbol{H}_{\mathrm{R}2}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{y}_{\mathrm{R}} + \boldsymbol{n}_2^{(2)}, \\ =& \boldsymbol{H}_{R2}\boldsymbol{F}_R\boldsymbol{H}_{2R}\boldsymbol{f}_2 s_2 + \boldsymbol{H}_{R2}\boldsymbol{F}_R\boldsymbol{H}_{1R}\boldsymbol{f}_1 s_1 \\ &+ \boldsymbol{H}_{R2}\boldsymbol{F}_R\boldsymbol{n}_R + \boldsymbol{n}_2^{(2)} \end{aligned}$$

where $\boldsymbol{F}_{\mathrm{R}} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ is the relay amplification matrix. Applying the linear receive filters $\boldsymbol{w}_1 \in \mathbb{C}^{2M_{\mathrm{U},1} \times 1}$ and $\boldsymbol{w}_2 \in \mathbb{C}^{2M_{\mathrm{U},2} \times 1}$ at each UT, we finally get the received signals expressed in equations (1) and (2) (shown on the top of the next page), where $\boldsymbol{n}_1^{(i)}$, $\boldsymbol{n}_2^{(i)}$ and $\boldsymbol{n}_{\mathrm{R}}$ contain independent, identically distributed additive white Gaussian noise samples with the variance $\sigma_n^2$. It can be seen that the system model can be simplified to a classical two-user IC based on the equivalent channels $\boldsymbol{H}_1, \boldsymbol{H}_2, \boldsymbol{G}_1$, and $\boldsymbol{G}_2$, which requires the relay precoder $\boldsymbol{F}_{\mathrm{R}}$ to be designed first.

### 2.1 Relay Amplification Matrix Design

In the section, we propose a relay amplification matrix design so that the IRC is converted to an IC. To start, we derive a relay amplification matrix which is inspired by the algebraic norm maximization method (ANOMAX) [8]. Since $\boldsymbol{H}_1$ and $\boldsymbol{H}_2$ are the equivalent channels for the desired signals, maximizing the norm $\beta^2 \|\boldsymbol{H}_1\|_F^2 + (1-\beta)^2 \|\boldsymbol{H}_2\|_F^2$ enhances the desired signal's energy and therefore improves the SNR, where $\beta$ is the weighting factor ranging between 0 and 1. The solution of the one-way ANOMAX (OW-ANOMAX) is given by

$$\begin{aligned} &\underset{\boldsymbol{F}_{\mathrm{R},n}, \|\boldsymbol{F}_{\mathrm{R},n}\|_{\mathrm{F}}=1}{\arg\max} \quad \beta^2 \|\boldsymbol{H}_1\|_F^2 + (1-\beta)^2 \|\boldsymbol{H}_2\|_F^2 \\ =& \underset{\boldsymbol{F}_{\mathrm{R},n}, \|\boldsymbol{F}_{\mathrm{R},n}\|_{\mathrm{F}}=1}{\arg\max} \quad \beta^2 \|\boldsymbol{H}_{\mathrm{R}1}\boldsymbol{F}_{\mathrm{R},n}\boldsymbol{H}_{1\mathrm{R}}\|_F^2 + (1-\beta)^2 \|\boldsymbol{H}_{\mathrm{R}2}\boldsymbol{F}_{\mathrm{R},n}\boldsymbol{H}_{2\mathrm{R}}\|_F^2 \\ =& \underset{\boldsymbol{F}_{\mathrm{R},n}, \|\boldsymbol{F}_{\mathrm{R},n}\|_{\mathrm{F}}=1}{\arg\max} \left\| \begin{bmatrix} \beta(\boldsymbol{H}_{1R}^{\mathrm{T}} \otimes \boldsymbol{H}_{R1}) \\ (1-\beta)(\boldsymbol{H}_{2R}^{\mathrm{T}} \otimes \boldsymbol{H}_{R2}) \end{bmatrix} \mathrm{vec}\{\boldsymbol{F}_R\} \right\|_2^2 \\ =& \underset{\boldsymbol{F}_{\mathrm{R},n}, \|\boldsymbol{F}_{\mathrm{R},n}\|_{\mathrm{F}}=1}{\arg\max} \Big\| \underbrace{[\beta(\boldsymbol{H}_{1\mathrm{R}} \otimes \boldsymbol{H}_{\mathrm{R}1}^{\mathrm{T}}), (1-\beta)(\boldsymbol{H}_{2\mathrm{R}} \otimes \boldsymbol{H}_{\mathrm{R}2}^{\mathrm{T}})]^{\mathrm{T}}}_{\boldsymbol{K}_\beta} \underbrace{\mathrm{vec}\{\boldsymbol{F}_{\mathrm{R},n}\}}_{\boldsymbol{f}_{\mathrm{R}}} \Big\|_2^2 \\ =& \underset{\boldsymbol{f}_{\mathrm{R}}, \|\boldsymbol{f}_{\mathrm{R}}\|_2=1}{\arg\max} \frac{\boldsymbol{f}_{\mathrm{R}}^{\mathrm{H}} \boldsymbol{K}_\beta^* \boldsymbol{K}_\beta^{\mathrm{T}} \boldsymbol{f}_{\mathrm{R}}}{\boldsymbol{f}_{\mathrm{R}}^{\mathrm{H}} \boldsymbol{f}_{\mathrm{R}}} \\ =& \lambda_{\max}(\boldsymbol{K}_\beta^* \boldsymbol{K}_\beta^{\mathrm{T}}) \end{aligned}$$

Here, the Kronecker product between two matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ is symbolized by $\boldsymbol{A} \otimes \boldsymbol{B}$ and $\boldsymbol{K}_\beta$ is defined as $\boldsymbol{K}_\beta = [\beta(\boldsymbol{H}_{1\mathrm{R}} \otimes \boldsymbol{H}_{\mathrm{R}1}^{\mathrm{T}}), (1-\beta)(\boldsymbol{H}_{2\mathrm{R}} \otimes \boldsymbol{H}_{\mathrm{R}2}^{\mathrm{T}})]$. By performing a singular value decomposition (SVD) $\boldsymbol{K}_\beta = \boldsymbol{U}_\beta \cdot \boldsymbol{\Sigma}_\beta \cdot \boldsymbol{V}_\beta^{\mathrm{H}}$, the vectorized relay amplification matrix is designed as $\boldsymbol{f}_{\mathrm{R}} = \mathrm{vec}\{\boldsymbol{F}_{\mathrm{R},n}\} = \boldsymbol{u}_1^*$, where $\boldsymbol{u}_1$ is the first column of $\boldsymbol{U}_\beta$, i.e., the dominant left singular vector of $\boldsymbol{K}_\beta$. The normalized relay amplification matrix is obtained as $\boldsymbol{F}_{\mathrm{R},n} = \mathrm{unvec}\{\boldsymbol{f}_{\mathrm{R}}\}$ and we compute $\boldsymbol{F}_{\mathrm{R}}$ as $\boldsymbol{F}_{\mathrm{R}} = \gamma \boldsymbol{F}_{\mathrm{R},n}$, where $\gamma$ is a scalar to fulfill the transmit power constraint at the relay. There are also other alternatives which are inspired by well-known two-way relaying strategies as follows.

- Dual Channel Matching (DCM) [9]
  $\tilde{\boldsymbol{F}}_{\mathrm{R}} = \boldsymbol{H}_{\mathrm{R}1}^{\mathrm{H}} \boldsymbol{H}_{1\mathrm{R}}^{\mathrm{H}} + \boldsymbol{H}_{\mathrm{R}2}^{\mathrm{H}} \boldsymbol{H}_{2\mathrm{R}}^{\mathrm{H}}$
- Discrete Fourier Transform (DFT) matrix
  $\tilde{\boldsymbol{F}}_{\mathrm{R}} = \mathrm{DFT}(\boldsymbol{I}_{M_{\mathrm{R}}})$
- MMSE [10]
  $\tilde{\boldsymbol{F}}_{\mathrm{R}} = \boldsymbol{F}_{\mathrm{R,Tx}} \boldsymbol{F}_{\mathrm{R,Rx}}$
  $\boldsymbol{F}_{\mathrm{R,Rx}} = \boldsymbol{H}_{\mathrm{Rx}}^{\mathrm{H}} (\boldsymbol{H}_{\mathrm{Rx}} \boldsymbol{H}_{\mathrm{Rx}}^{\mathrm{H}} + \frac{\sigma_n^2}{P_{\mathrm{T}1} + P_{\mathrm{T}2}} \boldsymbol{I}_{M_{\mathrm{R}}})^{-1}$
  $\boldsymbol{F}_{\mathrm{R,Tx}} = (\boldsymbol{H}_{\mathrm{Tx}}^{\mathrm{H}} \boldsymbol{H}_{\mathrm{Tx}} + \frac{\sigma_n^2}{P_{\mathrm{T}1} + P_{\mathrm{T}2}} \boldsymbol{I}_{M_{\mathrm{R}}})^{-1} \boldsymbol{H}_{\mathrm{Tx}}^{\mathrm{H}}$
  where $\boldsymbol{H}_{\mathrm{Tx}} = \begin{bmatrix} \boldsymbol{H}_{\mathrm{R}1} \\ \boldsymbol{H}_{\mathrm{R}2} \end{bmatrix}$ and $\boldsymbol{H}_{\mathrm{Rx}} = [\boldsymbol{H}_{1\mathrm{R}}, \boldsymbol{H}_{2\mathrm{R}}]$.
- ZF [10]
  $\tilde{\boldsymbol{F}}_{\mathrm{R}} = \boldsymbol{H}_{\mathrm{Rx}}^{+} \boldsymbol{H}_{\mathrm{Tx}}^{+}$
  The superscript $+$ represent the pseudo inverse. The same $\boldsymbol{H}_{\mathrm{Rx}}$ and $\boldsymbol{H}_{\mathrm{Tx}}$ are used as for MMSE.

We compute $\boldsymbol{F}_{\mathrm{R}}$ as $\boldsymbol{F}_{\mathrm{R}} = \gamma \boldsymbol{F}_{\mathrm{R},n}$, where $\boldsymbol{F}_{\mathrm{R},n}$ is the normalized relay amplification matrix of $\tilde{\boldsymbol{F}}_{\mathrm{R}}$ obtained by one of the aforementioned methods such that $||\boldsymbol{F}_{\mathrm{R},n}|| = 1$. For all the relay amplification matrices design mentioned above, the scalar $\gamma$ adjusts the transmit power level, such that the relay transmit power constraint is satisfied. Let $P_{\mathrm{T,R}}$ be the available transmit power at the relay. Then we can find $\gamma$ via the approximation $\|\gamma \boldsymbol{F}_{\mathrm{R,n}} \boldsymbol{y}_{\mathrm{R}}\|_2^2 \leq \gamma^2 (M_{\mathrm{T},1} M_{\mathrm{R}} P_{\mathrm{T}1} + M_{\mathrm{T},2} M_{\mathrm{R}} P_{\mathrm{T}2} + M_{\mathrm{R}} \sigma_n^2) = P_{\mathrm{T,R}}$, where $P_{\mathrm{T}1}$ and $P_{\mathrm{T}2}$ are the trans-

$$y_1 = \boldsymbol{w}_1^{\mathrm{H}} \begin{bmatrix} y_1^{(1)} \\ y_1^{(2)} \end{bmatrix} = \boldsymbol{w}_1^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{H}_{11} \\ \boldsymbol{H}_{\mathrm{R}1}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{H}_{1\mathrm{R}} \end{bmatrix}}_{\boldsymbol{H}_1} \boldsymbol{f}_1 s_1 + \boldsymbol{w}_1^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{H}_{21} \\ \boldsymbol{H}_{\mathrm{R}1}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{H}_{2\mathrm{R}} \end{bmatrix}}_{\boldsymbol{G}_1} \boldsymbol{f}_2 s_2 + \boldsymbol{w}_1^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{n}_1^{(1)} \\ \boldsymbol{H}_{\mathrm{R}1}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{n}_{\mathrm{R}} + \boldsymbol{n}_1^{(2)} \end{bmatrix}}_{\boldsymbol{e}_1} \tag{1}$$

$$y_2 = \boldsymbol{w}_2^{\mathrm{H}} \begin{bmatrix} y_2^{(1)} \\ y_2^{(2)} \end{bmatrix} = \boldsymbol{w}_2^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{H}_{22} \\ \boldsymbol{H}_{\mathrm{R}2}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{H}_{2\mathrm{R}} \end{bmatrix}}_{\boldsymbol{H}_2} \boldsymbol{f}_2 s_2 + \boldsymbol{w}_2^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{H}_{12} \\ \boldsymbol{H}_{\mathrm{R}2}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{H}_{1\mathrm{R}} \end{bmatrix}}_{\boldsymbol{G}_2} \boldsymbol{f}_1 s_1 + \boldsymbol{w}_2^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{n}_2^{(1)} \\ \boldsymbol{H}_{\mathrm{R}2}\boldsymbol{F}_{\mathrm{R}}\boldsymbol{n}_{\mathrm{R}} + \boldsymbol{n}_2^{(2)} \end{bmatrix}}_{\boldsymbol{e}_2} \tag{2}$$

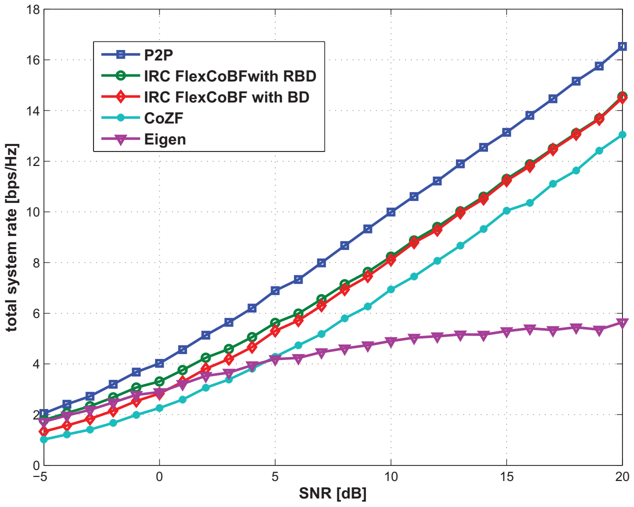

Figure 2: Sum rate vs SNR for the interference channel

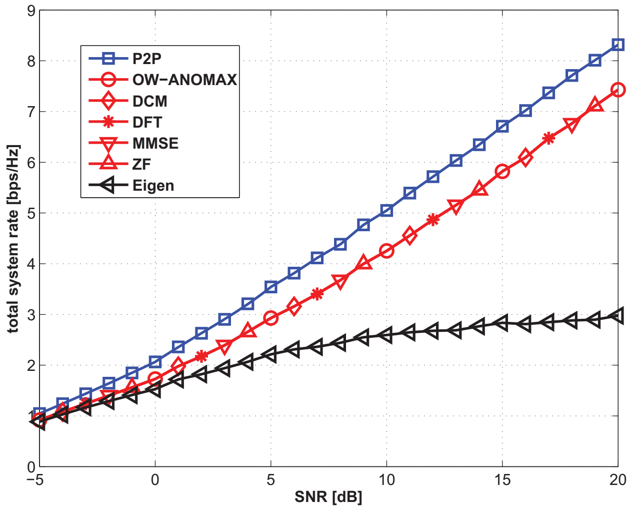

Figure 3: Sum rate of the interference relay channel for different relaying strategies

mit power of BS1 and BS2 respectively. For simplicity, we choose $\gamma$ as

$$\gamma = \sqrt{\frac{P_{\mathrm{T,R}}}{M_{\mathrm{T},1}M_{\mathrm{R}}P_{\mathrm{T}1} + M_{\mathrm{T},2}M_{\mathrm{R}}P_{\mathrm{T}2} + M_{\mathrm{R}}\sigma_n^2}}$$

### 2.2 Precoder Design at the BSs

After the design of $\boldsymbol{F}_{\mathrm{R}}$, all the equivalent channel matrices $\boldsymbol{H}_i$ and the interference matrices $\boldsymbol{G}_i$ can be estimated from the downlink dedicated pilot transmission. Then the IRC corresponds to a conventional IC model. We assume that $\boldsymbol{H}_i$ and $\boldsymbol{G}_i$ are available at the BSs. At this point, no path loss is considered.

A recent technique dealing with linear precoding design at the BSs for the IC is named zero-forcing coordinated beamforming (CoZF) [7], which forces all the interferences to be zero assuming maximum ratio combining (MRC) at the receiver $\boldsymbol{w}_k = \boldsymbol{H}_k\boldsymbol{f}_k$ for $k = 1,2$. The precoders are chosen as a generalized eigenvector of $\boldsymbol{G}_i^{\mathrm{H}}\boldsymbol{H}_i$ and $\boldsymbol{H}_j^{\mathrm{H}}\boldsymbol{G}_j$. Although simple, this method has the dimensionality constraint that $M_{\mathrm{T},i} \leq M_{\mathrm{U},j}$ due to the full rank requirement of these equivalent channel matrices.

Taking [7] as a benchmark, we propose a method called flexible coordinated beamforming for the interference relay channel (IRC FlexCoBF) to improve the system sum rate performance and relax the dimensionality constraint. The original FlexCoBF [6] has been designed to iteratively suppress the inter-user interferences on the downlink of the multi-user MIMO systems, which utilizes either block diagonalization (BD) [11] or regularized block diagonalization (RBD) [12] at the transmitter combined with MRC at the receiver. Inspired by this idea, we derive a method suitable for the IC.

To start, the receive beamformer $\boldsymbol{w}_1$, $\boldsymbol{w}_2$ are randomly initialized. In the following, we sketch the design of $\boldsymbol{f}_2$ ($\boldsymbol{f}_1$ is designed analogously). If BD is applied at the BS2, we take the SVD of the equivalent interference channel $\tilde{\boldsymbol{g}}_1^{\mathrm{T}} = \boldsymbol{v}_1^{\mathrm{H}}\boldsymbol{G}_1 = 1 \cdot \tilde{\boldsymbol{\sigma}}_1^{\mathrm{T}} \cdot [\tilde{\boldsymbol{v}}_1^{(1)}\,\tilde{\boldsymbol{V}}_1^{(0)}]^{\mathrm{H}}$, where the signal subspace and the null subspace of $\tilde{\boldsymbol{g}}_1^{\mathrm{T}}$ is spanned by the columns of $\tilde{\boldsymbol{v}}_1^{(1)} \in \mathbb{C}^{M_T}$ and $\tilde{\boldsymbol{V}}_1^{(0)} \in \mathbb{C}^{M_T \times (M_T - 1)}$, respectively. In order to maximize the throughput of the second transceiver pair under zero-interference constraint to user 1, we take the SVD on the equivalent channel $\boldsymbol{v}_2^{\mathrm{H}}\boldsymbol{H}_2\tilde{\boldsymbol{V}}_1^{(0)} = 1 \cdot \tilde{\boldsymbol{\sigma}}_2^{\mathrm{T}} \cdot \tilde{\boldsymbol{V}}_2^{\mathrm{H}}$ and the precoder $\boldsymbol{w}_2$ is obtained as $\boldsymbol{w}_2 = \tilde{\boldsymbol{V}}_1^{(0)}\tilde{\boldsymbol{v}}_2$, where $\tilde{\boldsymbol{v}}_2$ is the dominant singular vector of $\tilde{\boldsymbol{V}}_2$. On the other hand, when RBD is used at the transmitter, the precoder is designed in two steps and we take the design of $\boldsymbol{f}_2$ as an example. Let $\boldsymbol{f}_2 = \alpha\boldsymbol{F}_{2a}\boldsymbol{f}_{2b}$, where $\boldsymbol{F}_{2a}$ is used to suppress the in-

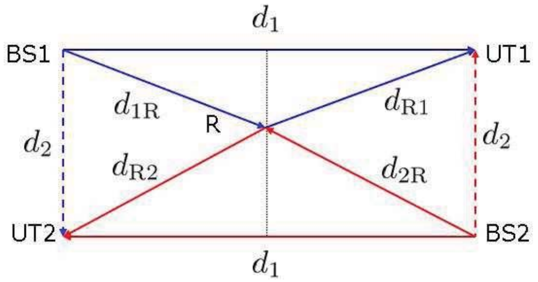

Figure 4: Path loss model of the interference relay channel

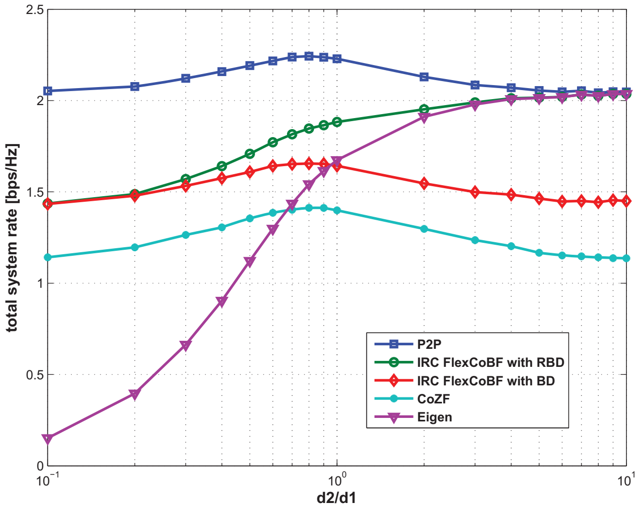

Figure 5: Sum rate for interference relay channel path loss model at SNR = 0 dB

terference and $\boldsymbol{f}_{2b}$ facilitates the sum rate optimization of the first link. Assuming that $||\boldsymbol{f}_{2b}|| = 1$ and that the $s_i$ are temporally uncorrelated with zero mean and unit variance $E\{|s_i|^2\} = 1$, we have $\alpha^2||\boldsymbol{F}_{2a}\boldsymbol{f}_{2b}s_i||^2 = \alpha^2||\boldsymbol{F}_{2a}||^2 \leq P_{\mathrm{T}2}$. Therefore, we choose $\alpha = P_{\mathrm{T}2}/\mathrm{tr}\{\boldsymbol{F}_{2a}\boldsymbol{F}_{2a}^{\mathrm{H}}\}$ with $P_{\mathrm{T}2}$ denoting the transmit power of BS2. After computing the SVD of $\tilde{\boldsymbol{g}}_1 = \boldsymbol{w}_1^{\mathrm{H}}\boldsymbol{G}_1 = 1 \cdot \tilde{\boldsymbol{\sigma}}_1^{\mathrm{T}} \cdot \tilde{\boldsymbol{V}}_1^{\mathrm{H}}$, we get $\boldsymbol{F}_{2a} = \boldsymbol{M}_{2a}\boldsymbol{D}_{2a}$, where $\boldsymbol{M}_{2a} = \tilde{\boldsymbol{V}}_1$ and $\boldsymbol{D}_{2a} = (\tilde{\boldsymbol{\sigma}}_1\tilde{\boldsymbol{\sigma}}_1^{\mathrm{T}} + \frac{M_{\mathrm{U},1}\sigma_n^2}{P_{\mathrm{T}2}}\boldsymbol{I}_{M_{\mathrm{T},2}})^{-1/2}$ is a diagonal power loading matrix. The vector $\boldsymbol{f}_{2b}$ is obtained from the SVD of the equivalent channel $\boldsymbol{w}_2^{\mathrm{H}}\boldsymbol{H}_2\boldsymbol{F}_{2a} = 1 \cdot \tilde{\boldsymbol{\sigma}}_2^{\mathrm{T}} \cdot \tilde{\boldsymbol{V}}_2^{\mathrm{H}}$ as $\boldsymbol{f}_{2b} = \boldsymbol{v}_2$, where $\boldsymbol{v}_2$ is the right dominant singular vector of $\boldsymbol{w}_2^{\mathrm{H}}\boldsymbol{H}_2\boldsymbol{F}_{2a}$. A similar procedure can be obtained for $\boldsymbol{f}_1$. With this transmit precoder obtained from either BD or RBD, the receive filter is updated as $\boldsymbol{w}_j = \boldsymbol{H}_j\boldsymbol{f}_j$ for the next iteration. The procedure continues until the stopping criterion is fulfilled, i.e., the interference is below a predefined threshold.

## 3. SIMULATION RESULTS

We assume that perfect link adaptation and perfect synchronization can be achieved. Each element of the $\boldsymbol{H}_{ij}$ is a zero mean circularly symmetric complex Gaussian random variable with unit variance $\mathcal{CN}(0,1)$. The transmit power of the BSs is $P_{\mathrm{T}1} = P_{\mathrm{T}2} = P_{\mathrm{T}}$ and the SNR is defined as $P_{\mathrm{T}}/\sigma_n^2$.

The sum rate performance of the IC is given in Fig. 2 including IRC FlexCoBF as well as CoZF. Both transmitters and receivers are equipped with 2 antennas. As a reference, we also include an upper bound (P2P transmission) and a reference scheme (Eigen), by performing eigen-beamforming for both links without and with taking the interference into account, respectively. It is observed that IRC FlexCoBF with either RBD or BD performs much better than CoZF within all SNR ranges. Especially at low SNRs, CoZF performs even worse than Eigen. IRC FlexCoBF RBD improves the sum rate compared to BD because it allows some residual interferences to balance with the noise enhancement. After that by fixing the precoders at the BSs using IRC FlexCoBF RBD, different relaying strategies are compared, as shown in Fig. 3. We observe that all the proposed AF relay precoders almost give the same sum rate, of which OW-ANOMAX with $\beta = 0.5$ performs slightly better than others. With respect to the complexity consideration, we propose to use the DFT as the relay amplification matrix and use it in the following simulations.

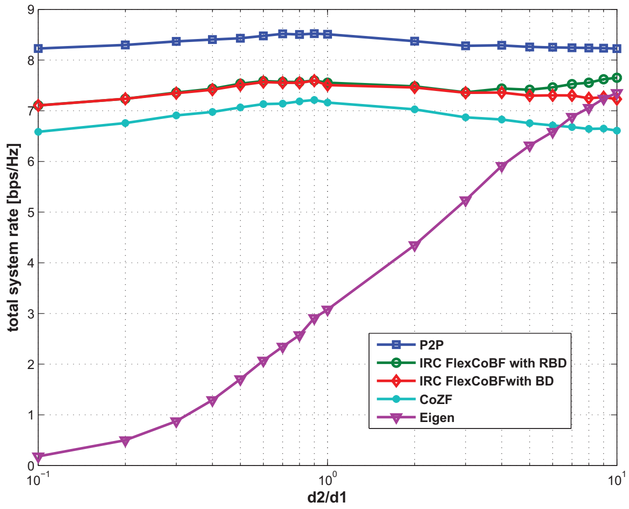

Figure 6: Sum rate for interference relay channel path loss model at SNR = 20 dB

Furthermore, a path loss model is introduced to test the robustness to the interference of the proposed method compared to the CoZF in [7]. As shown in Fig. 4, the distance between the BSs and the UTs is $d_1$ and that the distance between these two interfering links is $d_2$. The relay is assumed to be in the centre of the two interfering links, which means $d_{1\mathrm{R}} = d_{\mathrm{R}1} = \frac{\sqrt{d_1^2+d_2^2}}{2}$ and $d_{2\mathrm{R}} = d_{\mathrm{R}2} = \frac{\sqrt{d_1^2+d_2^2}}{2}$. The channel is constructed by scaling the channel matrix by $d^{-\frac{\alpha}{2}}$, where $\alpha$ is the path loss exponent. $\boldsymbol{H}_{ij,\mathrm{PL}} = \boldsymbol{H}_{ij} \cdot d^{-\frac{\alpha}{2}}$ The path loss model for interference relay channel is shown in Fig. 4.

By using the DFT as the relay amplification matrix with $M_{\mathrm{R}} = 2$, Fig. 5 and Fig. 6 depicts the sum rate depending on the ratio of $d_2/d_1$ for the path loss model of the IRC for SNR = 0 dB and SNR = 20 dB, respectively. When $d_2/d_1$ is small, it means that strong interferences exist between the two transceiver pairs. On the other hand, a larger $d_2/d_1$ results in weaker interferences. It can be seen that all types of the precoders except Eigen are resistant to the interferences. Furthermore, as $d_2/d_1$ increases, the gap between IRC FlexCoBF RBD and IRC FlexCoBF BD as well as CoZF is even larger due to a smaller loss caused by the interference miti-

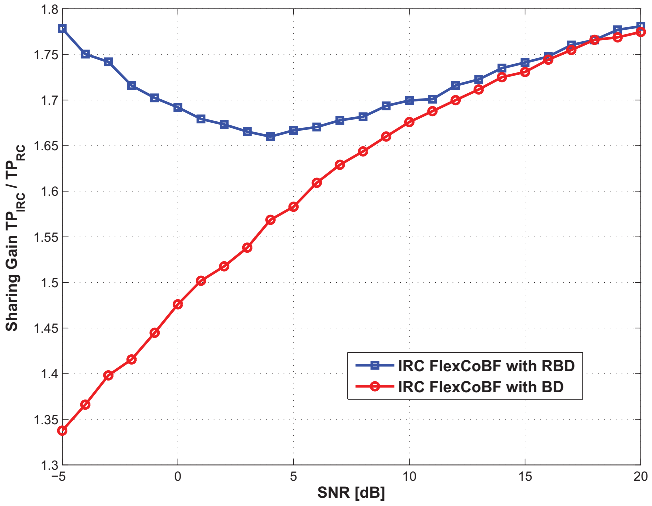

Figure 7: Sharing gain of the IRC over the RC

gation. When the interference is quite small, IRC FlexCoBF converges to the P2P bound.

We refer to the ratio of throughput (TP) $TP_{IRC}$ / $TP_{RC}$ as the *sharing gain* due to the use of the shared relay instead of accessing the relay in a TDMA mode. This sharing gain of the IRC over the RC is shown in Fig. 7, where IRC FlexCoBF and Eigen are applied at the BS for the IRC and the RC, respectively. It can be seen that the IRC utilizing either IRC FlexCoBF RBD or IRC FlexCoBF BD provides a sharing gain over RC which uses the relay exclusively. For IRC FlexCoBF BD, the sharing gain becomes larger as the SNR increases. When IRC FlexCoBF RBD is applied, there is even an improvement at low SNRs due to the regularization of RBD. This shows that relay sharing is more advantageous compared to the exclusive use of the infrastructure resources (i.e., the relay in the considered scenario).

## 4. CONCLUSION

In this paper, the linear precoding design for the MIMO interference relay channel is studied, where an amplify-and-forward relay with multiple antennas is shared between two operators. Various relaying strategies are investigated for this scenario. First we consider the conversion of the interference relay channel (IRC) to the interference channel (IC), where we propose to use the DFT matrix as the relay amplification matrix. After that we recommend the precoding method IRC flexible coordinated beamforming (FlexCoBF) at the BSs, which achieves a better sum rate performance compared to coordinated zero-forcing (CoZF) beamforming as well as eigen-beamforming [7]. IRC FlexCoBF is also more robust to the interference. Last but not least, the sum rate performance of the IRC is compared to the relay channel and there exists a large sharing gain, which strongly supports the use of a shared relay instead of operating in the time division multiple access (TDMA) mode.

### Acknowledgments

This work has been performed in the framework of the European research project SAPHYRE (www.SAPHYRE.eu), which is partly funded by the European Union.

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