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An efficient beamforming design for multipair full-duplex relaying systems[☆,☆☆]

Hyeon Min Kim[a], Van-Dinh Nguyen[a], Oh-Soon Shin[b,*]

[a] Department of ICMC Convergence Technology, Soongsil University, Seoul 06978, Republic of Korea
[b] School of Electronic Engineering & Department of ICMC Convergence Technology, Soongsil University, Seoul 06978, Republic of Korea

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Abstract

We consider a decode-and-forward full-duplex relaying system for multiple pairs of users. Our objective is to maximize the minimum achievable rate for all user pairs under the transmit power constraints. We propose an iterative algorithm to solve the nonconvex max–min problem. In particular, the original problem is converted into successive convex programs by using an inner approximation method such that each iteration involves only a simple convex quadratic program. We show that the proposed algorithm improves achievement of the objective iteratively while guaranteeing convergence. Simulation results demonstrate that the proposed algorithm provides higher rates than both half-duplex and full-duplex relaying based on zero-forcing do.

Keywords: Full-duplex relaying; Multipair relaying; Nonconvex programming; Self-interference; Transmit beamforming

1. Introduction

Using a relay in a wireless system allows us to extend the communication coverage and improve the throughput and the quality-of-service (QoS). Thus, relaying is a promising technique for next-generation wireless networks. Its use in LTE-Advanced networks has been studied intensively [1]. Relaying protocols can be classified into two main categories: amply-and-forward (AF) and decode-and-forward (DF). Although AF protocol design is easy to implement, it critically restricts the system performance. This is because AF protocol enhances both the signal and noise power when it amplifies the received signal [2]. On the other hand, DF protocol decodes the received data from the source node and forwards them to the destination node, providing a better performance than AF protocol does [3].

There are two approaches to relaying system transmission: half-duplex relaying (HDR) and full-duplex relaying (FDR). The HDR system uses different time slots or different frequencies for transmission and reception while the FDR system receives and transmits the information simultaneously on the same frequency. Therefore, FDR utilizes the spectrum resources more efficiently than HDR does. However, receiving and retransmitting the signals at the same time and over the same frequency causes self-interference (SI) between the transmit antennas and the receive antennas at the relay, which is an obstacle to FDR performance. As a result, a long-held assumption in wireless system design is that a relay is compatible with only the HDR technique [4].

In several recent studies, advances in SI cancellation techniques have shown the feasibility of FDR for relaying systems [5,6]. Nevertheless, most of the FDR research has focused on improving the system performance for a single pair, i.e., one source communicating with one destination [7–9]. Interestingly, a very recent study considered an FDR system of multipair users using zero-forcing for both the decoding and beamforming at the FDR (ZF/ZF) [10]. However, an FDR system using a ZF/ZF method is actually far from optimum and thus yields a very limited performance. Therefore, there is still much room to optimize FDR systems.

In this article, we consider the joint optimization of beamforming at the FDR system and power allocation at the source nodes to serve multipair users in an FDR system efficiently

* Corresponding author.
E-mail addresses: hminplus@ssu.ac.kr (H.M. Kim), nguyenvandinh@ssu.ac.kr (V.-D. Nguyen), osshin@ssu.ac.kr (O.-S. Shin).

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based on the DF protocol. The residual SI is also taken into account. In particular, we first establish a max–min optimization problem for all of the communication links for multipair users under the power constraints of both the sources and relay. Then, we propose a one-layer iterative algorithm based on a first-order inner approximation to obtain the optimal solution through sequential convex optimization. Finally, the performance of the method proposed for the FDR technique is evaluated and compared with those of the HDR and FDR techniques in [10].

The rest of this article is organized as follows. In Section 2, we describe a system model with explicit signals and formulate an optimization problem. In Section 3, we describe how to find an optimal solution based on an iterative method. Simulation results are presented in Section 4, and conclusions are drawn in Section 5.

Notation: Bold lower and upper case letters respectively represent vectors and matrices. $\mathbf{X}^H$, $\mathbf{X}^T$, and $\mathrm{tr}(\mathbf{X})$ are the Hermitian transpose, normal transpose, and trace of a matrix $\mathbf{X}$, respectively. $\|\cdot\|$ and $|\cdot|$ denote the Euclidean norm of a matrix or vector and the absolute value of a complex scalar, respectively. $\mathbf{I}_N$ represents an $N \times N$ identity matrix. $\mathbf{x} \sim \mathcal{CN}(\boldsymbol{\eta}, \mathbf{Z})$ means that $\mathbf{x}$ is a random vector following a circularly-symmetric complex Gaussian (CSCG) distribution with mean vector $\boldsymbol{\eta}$ and covariance matrix $\mathbf{Z}$. $\mathbb{E}[\cdot]$ denotes the statistical expectation. The notations $\mathbf{X} \succeq \mathbf{0}$ and $\mathbf{X} \succ \mathbf{0}$ mean that the matrix $\mathbf{X}$ is positive semi-definite and positive definite, respectively. $\Re\{\cdot\}$ represents the real part of a complex number.

2. System model and optimization problem formulation

2.1. Signal model

We consider a multipair DF relaying system in which K source nodes communicate with K destination nodes separately via an FDR, as illustrated in Fig. 1. All source and destination nodes are equipped with a single antenna, while the FDR is equipped with a total of $N_{\text{tx}} + N_{\text{rx}}$ antennas. The FDR uses N_{rx} antennas to receive the sources' signals and N_{tx} antennas to transmit these signals to the destinations as part of the full-duplex operation. In Fig. 1, S_k and D_k represent the kth source node and the kth destination node, respectively. It is assumed that no direct link between any S_k and D_k exists due to large path loss and/or severe shadowing. All channels are assumed to follow independent quasi-static flat fading, i.e., remain constant during communication time slot T but change independently from one block to another. The channel state information (CSI) is assumed to be perfectly known at both the BS and users.

In each resource block, all K sources transmit their signals, denoted as $x_k, \forall k$ with $\mathbb{E}\{|x_k|^2\} = 1$, to the FDR, and then, the FDR decodes and forwards the signals, denoted by $s_k, \forall k$ with $\mathbb{E}\{|s_k|^2\} = 1$, to all K destinations simultaneously. At the FDR, the signals are precoded prior to being transmitted to the destination. Then, the received signals at the FDR and at D_k can be written as

$$\mathbf{y}_{\mathsf{FDR}} = \sum_{k=1}^{K} p_k \mathbf{h}_k x_k + \sqrt{\rho} \sum_{k=1}^{K} \mathbf{G}_{\mathsf{SI}}^H \mathbf{w}_k s_k + \mathbf{n}_{\mathsf{FDR}}, \tag{1}$$

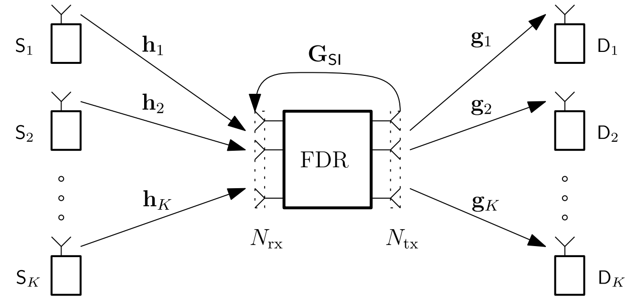

Fig. 1. An FDR system with multipair users.

and

$$y_{\mathsf{D}_k} = \mathbf{g}_k^H \mathbf{w}_k s_k + \sum_{i=1, i\neq k}^{K} \mathbf{g}_k^H \mathbf{w}_i s_i + n_{\mathsf{D}_k}, \quad \forall k, \tag{2}$$

respectively. $p_k \in \mathbb{C}$ and $\mathbf{h}_k \in \mathbb{C}^{N_{\text{rx}} \times 1}$ are the transmit power and the channel vector from S_k to the FDR, respectively. $\mathbf{g}_k \in \mathbb{C}^{N_{\text{tx}} \times 1}$ and $\mathbf{w}_k \in \mathbb{C}^{N_{\text{tx}} \times 1}$ are the transmit channel vector and the beamforming vector from the FDR to D_k, respectively. $n_{\mathsf{D}_k} \sim \mathcal{CN}(0, \sigma_k^2)$ and $\mathbf{n}_{\mathsf{FDR}} \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I})$ denote the additive white Gaussian noise (AWGN) at D_k and at the FDR, respectively. The term $\sqrt{\rho}\sum_{k=1}^{K} \mathbf{G}_{\mathsf{SI}}^H \mathbf{w}_k s_k$ in (1) represents the residual SI after all real-time cancellations [4] have taken place, where $\mathbf{G}_{\mathsf{SI}} \in \mathbb{C}^{N_{\text{tx}} \times N_{\text{rx}}}$ is a fading loop channel from the transmit antennas to the receive antennas at the FDR and $0 \leq \rho \leq 1$ is used to model the degree of residual SI propagation [11].

In the first phase, the minimum mean square error and successive interference cancellation (MMSE–SIC) receiver is adopted by the FDR to maximize the received signal-to-interference-plus-noise ratio (SINR) of S_k in (1). Correspondingly, the received SINR for x_k can be expressed as [12]

$$\gamma_k^{\mathsf{SR}}(\mathbf{w}, \mathbf{p}) = p_k^2 \mathbf{h}_k^H \Big(\sum_{j>k}^{K} p_j^2 \mathbf{h}_j \mathbf{h}_j^H + \rho \sum_{k=1}^{K} \mathbf{G}_{\mathsf{SI}}^H \mathbf{w}_k \mathbf{w}_k^H \mathbf{G}_{\mathsf{SI}} + \sigma^2 \mathbf{I} \Big)^{-1} \mathbf{h}_k, \tag{3}$$

where $\mathbf{w} \triangleq [\mathbf{w}_1^T, \mathbf{w}_2^T, \ldots, \mathbf{w}_K]^T$ and $\mathbf{p} \triangleq [p_1, p_2, \ldots, p_K]^T$. For simplicity, we assume that the decoding order follows the source indices, i.e., $k = 1, 2, \ldots, K$. Next, using (2), the SINR at D_k can be expressed as

$$\gamma_k^{\mathsf{RD}}(\mathbf{w}) = \frac{|\mathbf{g}_k^H \mathbf{w}_k|^2}{\sum_{i=1, i\neq k}^{K} |\mathbf{g}_k^H \mathbf{w}_i|^2 + \sigma_k^2}. \tag{4}$$

From (3), the information rate for the link $\mathsf{S}_k \to \mathsf{FDR}$ (in nats/s/Hz) is given as

$$R_k^{\mathsf{SR}}(\mathbf{w}, \mathbf{p}) = \ln\big(1 + \gamma_k^{\mathsf{SR}}(\mathbf{w}, \mathbf{p})\big), \tag{5}$$

and the information rate for the link $\mathsf{FDR} \to \mathsf{D}_k$ (also in nats/s/Hz) is given as

$$R_k^{\mathsf{RD}}(\mathbf{w}) = \ln\big(1 + \gamma_k^{\mathsf{RD}}(\mathbf{w})\big). \tag{6}$$