Joint Relay Processing and Power Control for Two-Way Relay Networks Under Individual SINR Constraints

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Abstract. This paper proposes an iterative algorithm, with which the relay processing matrix and power control can be realized jointly in two-way relay networks consisting of multiple pairs of single-antenna users and one multi-antenna relay station (RS). The users pairs in these networks exchange their information through the half-duplex RS. The joint processing scheme is formulated by including the design of the processing scheme at the RS and the transmit power of each node. Take the consideration of fairness among users, the scheme is written as an optimization problem which is formulated to minimize the total transmit power of all nodes subject to the individual signal to interference plus noise ratio (SINR) of each user. An iterative algorithm is proposed to solve the formulated non-convex joint optimization problem. The relay processing matrix is designed to maximize the SINR of each transmission link by using the uplink-downlink duality theory. In addition, theoretical analysis and simulation results demonstrate that with the given processing matrix at the RS, the total transmit power is a convex function with respect to the amplifying factor at the RS. The proposed algorithm is proved to converge efficiently.

Keywords: Two-way · Relay processing · Power control · Signal to interference plus noise ratio

1 Introduction

Two-way relay networks [1,2] have attracted much attention for its double spectrum efficiency comparing with conventional one-way relaying. In a two-way relaying, a bidirectional communication is established between two users, which takes two time slots. In the first time slot, users transmit signals to the relay station (RS) simultaneously. And in the second time slot, the RS processes the

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received signals and broadcast to all of the users. In [3], the capacity region of two-way relay networks with one pair of users and single RS is obtained. [4] extended the capacity region analysis to the case with multiple pairs of users. Resource allocation in two-way relaying systems has also been studied widely to improve the system performance. In [5], the optimal relay power allocation problem is investigated to maximize an arbitrary weighted sum rate of all users for a multiuser two-way relaying system with decode-and-forward (DF), amplify-and-forward (AF) and compress-and-forward (CF) protocols. The optimal resource allocation to maximize the sum rate for a two-way relay orthogonal frequency-division multiple access (OFDMA) system is studied in [6].

Multiple-input multiple-output (MIMO) can improve the system capacity or reliability of data transmission without additional power or bandwidth expenditure [7]. It has been widely studied in two-way relaying. For the network with one pair of users and multiple single-antenna RS, two optimal distributed beamforming methods at the RS are studied in [8]. One is to minimize the total transmit power whereas the other is to maximize the minimum of the two transceiver signal to noise ratios (SNRs) with the total power constraint. And the problem of maximizing the minimum of the two SNRs is also discussed with per-node power constraints by joint power control and distributed beamforming in [9]. In addition, the achievable rate region of such kind of networks via designing joint power allocation and collaborative beamforming scheme is studied in [10]. [11] considers a two-way relay network consisting of multiple pairs of users and multiple single-antenna relays and get two closed-form expressions for zero-forcing beamforming weights. One scheme is to null out every inter-pair interference and the other one is to cancel the total inter-pair interference. In [12], a low-complexity joint beamforming and power management scheme is proposed for a two-way relay network with one pair of multiantenna users and one multi-antenna RS to maximize the sum-rate and minimize the total transmission power. With the same network structure, [13] proposes a beamforming scheme with limited feedback. For the network with multiple pairs of users and one multi-antenna RS, relay processing based on zero forcing (ZF) and minimum mean square error (MMSE) criteria is studied in [14], and two power control strategies are proposed for ZF system to achieve fairness among all users and the maximum system SNR. In [15], a joint power allocation and beamforming is proposed to minimize the MSE by a iterative algorithm. In [16], a iterative algorithm is proposed to minimize the total transmit power of users with employing MMSE relay processing scheme. [17] proposed the signal to interference plus noise ratio (SINR) balancing and interference minimization relay beamforming schemes with imperfect channel state information for an cognitive relay network consisting of a secondary network with multiple cognitive relay nodes and a primary network.

In this paper, we focus on a multiuser two-way relay system with a multi-antenna RS. Considering the fairness among all users and energy efficiency, we try to minimize the total transmit power of all nodes in the same time satisfying the SINR requirements of each user. The problem is formulated as joint optimizing the relay processing matrix and the power control policy. As the joint optimization problem is non-convex, an iterative algorithm is proposed to solve the problem. The relay processing matrix is obtained to maximize the SINR of each user by using the uplink-downlink duality theory, and with this given processing matrix, the total transmit power is a convex function with respect to the amplifying factor at the RS. Simulations show that the algorithm converge efficiently and can minimize the total transmit power under the target SINRs for users.

In the text followed, matrices and vectors are denoted by bold upper- and lower-case letters. $tr(\cdot)$, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote trace of a matrix, transpose and complex conjugate transpose of a matrix, respectively. $|\cdot|$ and $\|\cdot\|_2$ denote the absolute value and Euclidian norm, respectively.

2 System Model

Consider a two-way relay network which consists of K pairs of users and a RS, as shown in Fig. 1. The RS is equipped with $N_r > 1$ antennas while each user has a single antenna. Each pair of users exchange their information via the RS. Without loss of generality, we assume $user_{2i}$ and $user_{2i-1}, i \in \{1, 2, \cdots, K\}$ are two users exchanging their information via the RS. Denote $\boldsymbol{h}_k \in \mathbb{C}^N, k \in \{1, 2, \cdots, 2K\}$ as the channel vector from $user_k$ to the RS.

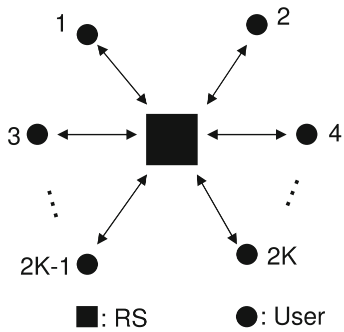

Fig. 1. A two-way relay network with K pairs of users

In the first phase, users transmit signals to the relay station simultaneously. The received signal at the relay station can be written as

$$\boldsymbol{r} = \boldsymbol{H}\sqrt{\boldsymbol{P}}\boldsymbol{s} + \boldsymbol{n}_r \in \mathbb{C}^N, \quad (1)$$

where $\boldsymbol{s} = [s_1, \ldots, s_{2K}]$ is the transmitted signals with unit power from all users. $\boldsymbol{P} = diag\{P_1, \cdots, P_{2K}\}$ accounts for power loading. $\boldsymbol{H} = [\boldsymbol{h}_1, \cdots, \boldsymbol{h}_{2K}] \in \mathbb{C}^{N_r \times 2K}$ is the channel matrix obtained by stacking all channel vectors seen from users to the RS. Besides, $\boldsymbol{n}_r \in \mathbb{C}^{N_r}$ is the additive white Gaussian noise with zero mean and variance $E[\boldsymbol{n}_r \boldsymbol{n}_r^{\mathrm{H}}] = \mathbf{I}\sigma^2$.

In the second phase, the signals are first processed at the RS, which can be modelled as

$$\boldsymbol{x} = \beta \boldsymbol{V} \boldsymbol{r}, \tag{2}$$

where β and $\boldsymbol{V} \in \mathbb{C}^{N_r \times N_r}$ are the amplifying factor and the processing matrix at the RS, respectively. The relay processing matrix is designed to perform data exchanging between a user pair and to suppress inter- and intra-pair interference. Then, the transmit power at the RS can be written as

$$P_r = \beta^2 tr(\boldsymbol{V}\boldsymbol{\Phi}\boldsymbol{V}^{\mathrm{H}}), \tag{3}$$

where P_r is the transmit power at the RS, $\boldsymbol{\Phi} = \boldsymbol{H}\boldsymbol{P}\boldsymbol{H}^{\mathrm{H}} + \sigma^2 \mathbf{I}$.

After processing, the RS broadcasts the processed signals to users. Due to the reciprocity of the channel between the uplink and downlink, the received signals at the users in this phase can be written as

$$\boldsymbol{y} = \boldsymbol{H}^{\mathrm{T}} \boldsymbol{x} + \boldsymbol{n}, \tag{4}$$

where $\boldsymbol{n} = [n_1, \cdots, n_{2K}]^{\mathrm{T}} \in \mathbb{C}^{2K \times 1}$ with $n_k, \forall k$ is Gaussian distributed with zero mean and variance σ^2. Then, the received noise power at user k is presented as

$$\sigma_k^2 = (\beta^2 \|\boldsymbol{h}_k^{\mathrm{T}} \boldsymbol{V}\|_2^2 + 1)\sigma^2. \tag{5}$$

Till now, we can write the expressions of SINR at $User_{2i-1}$ and $User_{2i}, \forall i$, which are given by

$$SINR_{2i-1} = \frac{\beta^2 |\boldsymbol{h}_{2i-1}^{\mathrm{T}} \boldsymbol{V} \boldsymbol{h}_{2i}|^2 P_{2i}}{\sum\limits_{j=1, j \neq 2i}^{2K} \beta^2 |\boldsymbol{h}_{2i-1}^{\mathrm{T}} \boldsymbol{V} \boldsymbol{h}_j|^2 P_j + \sigma_{2i-1}^2}, \tag{6}$$

and

$$SINR_{2i} = \frac{\beta^2 |\boldsymbol{h}_{2i}^{\mathrm{T}} \boldsymbol{V} \boldsymbol{h}_{2i-1}|^2 P_{2i-1}}{\sum\limits_{j=1, j \neq 2i-1}^{2K} \beta^2 |\boldsymbol{h}_{2i}^{\mathrm{T}} \boldsymbol{V} \boldsymbol{h}_j|^2 P_j + \sigma_{2i}^2}, \tag{7}$$

respectively.

3 Joint Power Control and Relay Processing Scheme

Considering the fairness among all users and the energy efficiency, the optimization problem is designed to minimize the total transmit power of users and the RS while satisfying SINR constraints at each user. Let $P_{total} = \sum\limits_{k=1}^{2K} P_k + P_r$, the optimization problem is written as

$$\begin{aligned} \{\boldsymbol{V}, \boldsymbol{p}, \beta\} = \arg \min_{\boldsymbol{V}, \boldsymbol{p}, \beta} \ & P_{total} \\ s.\ t. \qquad & SINR_k \geq \gamma_k, \end{aligned} \tag{8}$$

where $\boldsymbol{p} = diag\{\boldsymbol{P}\}$ and γ_k is the target SINR of user k. From the above expressions, we can get that when the processing matrix is given, the minimum total transmit power can only be obtained with equality in their constraints, which is written in matrix form as follows

$$\beta^2 \left(\boldsymbol{W} - \boldsymbol{D}\boldsymbol{\Psi}\right)\boldsymbol{p} = \boldsymbol{D}\left(\beta^2\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2\right), \tag{9}$$

where $\boldsymbol{W}$, $\boldsymbol{D}$, $\boldsymbol{\Psi}$ and $\boldsymbol{\sigma}$ are defined as follows

$$\boldsymbol{W} = blockdiag\left[\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}, \cdots, \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}\right] \in \mathbb{C}^{2K\times 2K}, \tag{10}$$

$$[\boldsymbol{D}]_{k,j} = \begin{cases} \frac{\gamma_k}{|\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{V}\boldsymbol{h}_{k+1}|^2}, & k = 2i-1, j = k \\ \frac{\gamma_k}{|\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{V}\boldsymbol{h}_{k-1}|^2}, & k = 2i, j = k \\ 0, & otherwise. \end{cases} \tag{11}$$

$$[\boldsymbol{\Psi}]_{k,j} = \begin{cases} |\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{V}\boldsymbol{h}_j|^2, & k = 2i-1, j \neq k+1 \\ |\boldsymbol{h}_k^{\mathrm{T}}\boldsymbol{V}\boldsymbol{h}_j|^2, & k = 2i, j \neq k-1 \\ 0, & k = 2i-1, j = k+1 \\ 0, & k = 2i, j = k-1. \end{cases} \tag{12}$$

$$\boldsymbol{\sigma}_1^2 = \left[\|\boldsymbol{h}_1^{\mathrm{T}}\boldsymbol{V}\|_2^2\sigma^2, \cdots, \|\boldsymbol{h}_{2K}^{\mathrm{T}}\boldsymbol{V}\|_2^2\sigma^2\right]^{\mathrm{T}}. \tag{13}$$

$$\boldsymbol{\sigma}_2^2 = \left[\sigma^2, \cdots, \sigma^2\right]^{\mathrm{T}} \tag{14}$$

Denote $\lambda_{max}(\cdot)$ as the maximum eigenvalue of a matrix. If $\lambda_{max}(\boldsymbol{D}\boldsymbol{\Phi}) < 1/\gamma$, Eq. (9) has feasible solution. It means that with this condition, there exist a positive power vector $\boldsymbol{p}$ and a positive value of β satisfying the SINR constraints. Given the processing matrix $\boldsymbol{V}$, it is easy to get the solution to this problem being

$$\boldsymbol{p} = \boldsymbol{\Omega}\left(\boldsymbol{\sigma}_1 + \beta^{-2}\boldsymbol{\sigma}_2\right). \tag{15}$$

where $\boldsymbol{\Omega} = \left(\boldsymbol{W} - \boldsymbol{D}\boldsymbol{\Psi}\right)^{-1}\boldsymbol{D}$. From the above equation, we get the solution is a function of β. To determine the value of $\boldsymbol{p}$ is to determine β. Substitute (15) into the objective function in (8), the optimization problem is then reduced to

$$\begin{aligned} \beta = \arg\min_{\beta}\ & \beta^2 tr\left(\boldsymbol{V}\boldsymbol{\Phi}\boldsymbol{V}^{\mathrm{H}}\right) + \mathbf{i}\boldsymbol{\Omega}\left(\boldsymbol{\sigma}_1 + \beta^{-2}\boldsymbol{\sigma}_2\right). \\ s.\ t. \quad & \beta > 0, \end{aligned} \tag{16}$$

where $\boldsymbol{i} = [1, \cdots, 1]^{\mathrm{T}}$. We can prove easily that the objective function in the above optimization problem is convex with respect to β. Then, its optimal solution is

$$\beta = \sqrt[4]{\mathbf{i}\boldsymbol{\Omega}\boldsymbol{\sigma}_2^2 / tr\left(\boldsymbol{V}\boldsymbol{\Phi}\boldsymbol{V}^{\mathrm{H}}\right)} \tag{17}$$

Substituting (17) into (15) and (3), we can get the transmit power at users and at the RS, respectively.

Given the obtained transmit power, the processing scheme at the RS can then be established. Firstly, we get the receive filter $\boldsymbol{V}_{rx}$ at RS, which is designed to maximize the individual SINRs of users in the first transmission phase. Define $\boldsymbol{R}_k = \boldsymbol{h}_k \boldsymbol{h}_k^{\mathrm{H}}/\sigma^2$, $\boldsymbol{Q} = \sum_{i=1, i\neq k}^{K} \boldsymbol{R}_i P_i + \mathbf{I}$. The optimization problem is formulated as follows

$$\boldsymbol{V}_{rx,k} = \arg\max_{\boldsymbol{V}_{rx,k}} \frac{\boldsymbol{V}_{rx,k}^{\mathrm{H}} \boldsymbol{R}_k \boldsymbol{V}_{rx,k}}{\boldsymbol{V}_{rx,k}^{\mathrm{H}} \boldsymbol{Q}_k \boldsymbol{V}_{rx,k}} \tag{18}$$

It is solved by the dominant generalized eigenvectors of the matrix pairs $(\boldsymbol{R}_k, \boldsymbol{Q}_k)$. Denote $\boldsymbol{V}_{tx}$ as the downlink transmit processing matrix at the RS. According to the uplink-downlink duality theory, it is easy to get $\boldsymbol{V}_{tx} = \boldsymbol{V}_{rx}^{\mathrm{T}}$. Then, the processing matrix at the RS can be written as

$$\boldsymbol{V} = \boldsymbol{V}_{tx} \boldsymbol{W} \boldsymbol{V}_{rx}. \tag{19}$$

After this two processes, the global optimal relay processing matrix and the power control strategy can be finally obtained via an iterative algorithm, which is summarized in Table 1.

Table 1. Iterative algorithm for the solution to the problem in (8)

1: Initialize: $t = 0, P_k(0) \neq 0, \forall k$
2: Obtain the processing scheme $\boldsymbol{V}(0)$ based on (19).
3: **Repeat**
3: $t \leftarrow t + 1$
4: Construct $\boldsymbol{\Psi}(t)$, $\boldsymbol{D}(t)$, $\boldsymbol{\Phi(t)}$ and $\boldsymbol{\sigma_1}(t)$ based on $\boldsymbol{V}(t-1)$.
5: **if** $\lambda_{max}\left(\boldsymbol{D}(t)\boldsymbol{\Psi(t)}\right) \geq 1$
6: Set $\gamma \leftarrow \gamma'$ such that $\lambda_{max}\left(\boldsymbol{D}(t)\Psi(t)\right) < 1$.
8: Update $\boldsymbol{D}(t)$.
9: **end if**
10: Obtain $\boldsymbol{p}(t), \beta(t)$ and the total transmit power $P_{total}(t)$.
11: **Until** $\frac{P_{total}(t) - P_{total}(t-1)}{P_{total}(t)} < \epsilon$

4 Computer Simulations

In this section, the performance of the proposed algorithm is investigated by computer simulations. To set up the system, we assume that there are 4 single antenna users and a 4 antennas RS. We also assume that the channel state information (CSI) between the RS and users are known perfectly at the RS. The elements of $\boldsymbol{h}_k$ is modelled as Rayleigh distributed variables with zero mean and unit variance. In all simulations, the noise variance $\sigma^2 = 10^{-3}$ and the stopping criterion ϵ is set to be 10^{-3}. The initial transmit power of users is 0.1 W. All results are obtained by taking the average of 1000 simulation runs.

We firstly investigate the convergence property of the proposed algorithm. The target SINRs are set to be the same, i.e. $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 10\,\text{dB}$. From Fig. 2, we can see that the transmit power of all nodes as well as the total transmit power converge to constants as the number of iterations increases. We have observed that the typical number of iterations is between 5 to 10, which is a fast convergence. The power assignments of users are the same as shown in Fig. 2 is due to the same assumptions on distances between users and the RS and the target SINRs. Different results will be achieved if those values are set to be different. In addition, the converged values of power is dependent on the initial transmit power.

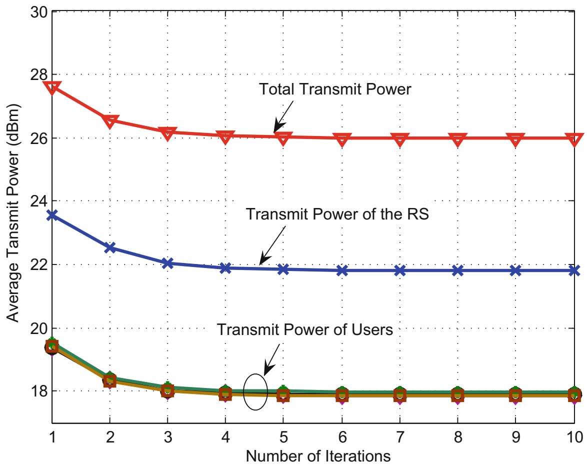

Fig. 2. Convergence of the average transmit power.

We then investigate how the amplifying factor β affect the total transmit power P_{total}. Results are shown in Fig. 3 showing that the value of β has a great impact on the total transmit power and telling that the total power can be minimized by carefully choosing the value of β. The results also tell that as β increases, the total transmit power first decreases, and then increases, showing that there must be a point the total power is minimum.

Figure 4 presents the converged total transmit power P_{total} and the user transmit power $P_k, \forall k$ as functions of the target SINRs $\{\gamma_1, \gamma_2, \gamma_3, \gamma_4\}$. It can be observed that when the target SINRs increases, the corresponding transmit power increases as expected. From the first and the third group data, we can see that when the target SINRs are the same, the transmit power assigned to users is also the same. Comparing the first group with the second group, we

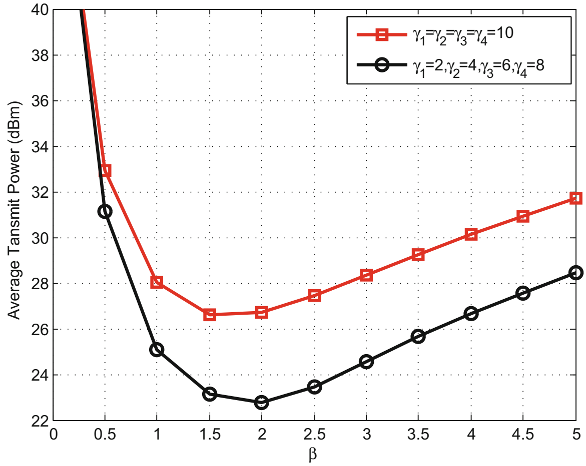

Fig. 3. Total transmit power versus relay amplifying factor β with different target SINRs $\{\gamma_1, \gamma_2, \gamma_3, \gamma_4\}$ (dB).

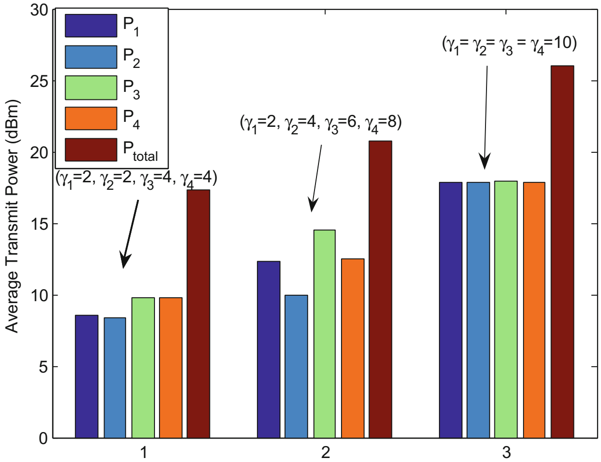

Fig. 4. Transmit power versus target SINRs $\{\gamma_1, \gamma_2, \gamma_3, \gamma_4\}$ (dB).

know that with the same target SINR of $user_1$ the transmit power of $user_2$ increases when the target SINRs of the others increase. The reason is that when the target SINRs of the rest users increase, the corresponding transmit power of their partners increases, then the interference power between users increases. $User_2$ has to raise its transmit power to guarantee the received SINR by $user_1$. In the first and the third group data, the values of total transmit power are about 20.78 dBm and 26.01 dBm, smaller than the minimum values given in Fig. 3, which are about 22.77 dBm and 26.70 dBm respectively.

5 Conclusions

In this paper, we have proposed an iterative algorithm to jointly optimize the processing matrix and power control policy in a two-way relay networks. Take the fairness among all users into account, the optimization problem is formulated to minimize the total transmit power of users and the RS while satisfying the SINR constraints of users. We get the processing matrix and the power control policy separately at first and then get the global optimal solution iteratively. The algorithm can converge quickly and the minimum total transmit power can be found efficiently with the proposed scheme.

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