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Transceiver Design for Multi-user Multi-antenna Two-way Relay Channels

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***Abstract*— In this paper, we design transceivers in a multi-user multi-antenna two-way relay system, where a single multi-antenna base station exchanges information with multiple users via a single multi-antenna relay station. We consider the half-duplex amplify-and-forward relay protocol. We aim to maximize the bidirectional sum rate under the constraint of no interference among different users. Suboptimal solutions to the problem that respectively maximizing the uplink and downlink rates are derived. We then introduce a threshold to balance the uplink and downlink rates so as to maximize the bidirectional sum rate. Simulation results show that the proposed scheme achieves considerably higher bidirectional sum rate than existing schemes.**

I. Introduction

Two-way relay (TWR) network has recently attracted significant interest, where two source nodes exchange information via a relay station (RS). The performance of two-way transmission using various relay protocols has been analyzed. In [1], transmission schemes respectively occupying 2, 3 and 4 time-slots are compared. It is shown that in most cases the 2 time-slot two-way transmission offers a higher spectral efficiency. For the 2 time-slot transmission, the outage performance of the amplify-and-forward (AF) and the decode-and-forward (DF) protocol are compared in [2]. It shows that the AF protocol outperforms the DF in symmetric channels, and the DF performs better only when the channel attenuation between the RS and the two source nodes are significantly different.

The single user pair TWR systems with only two source nodes are extended to the multiple user pairs systems in [3]–[6], where multiple user pairs exchange information via a single RS. Further in [7]–[9], the work is extended to multi-user multi-antenna TWR systems, where a multi-antenna base station (BS) exchanges N_U data streams with N_U users via a single multi-antenna RS. The overall transmission takes place in two phases. In the first phase, the BS transmits N_U different downlink signals for N_U users and the N_U users simultaneously transmit their own uplink signals for the BS. The RS receives all the uplink and downlink signals. In the second phase, the RS processes its received signals and forwards them to the BS and multiple users. Since there is no cooperation among users, the BS and RS processing has to ensure that there is no interference among different users.

In this paper, we focus on the linear transceiver design for eliminating the inter-user interference in such systems and we consider the AF protocol. There are two commonly used linear precoding schemes in our considered systems. One is the ZF scheme [7], and the other is the signal space alignment (SA) scheme [8], [9]. In the ZF approach, the RS uses the ZF technique to separate the N_U uplink and N_U downlink signals. It needs at least $2N_U$ antennas at the RS to separate N_U pairs of uplink and downlink signals. In the SA scheme, it assumes that the BS knows the channel between itself and the RS, and that between the RS and users. Using these channel state information, the BS performs signal projecting, so that its transmitted downlink signal for each user arrives at the RS on the same direction of the uplink signal from the same user. Then the RS receives N_U superimposed signals, each of which is the combination of each user's uplink and downlink signals. The RS only needs N_U antennas to separate these superimposed signals and then forwards them to their corresponding destinations. After receiving the combination of its uplink and downlink signal, each user removes its transmitted uplink signal and obtain its desired downlink signal. Compared with the ZF scheme, this SA scheme reduces the required RS antenna number almost by half.

In this paper, we design the transceiver structure to further improve the sum rate of multi-user multi-antenna TWR systems. We aim to maximize the bidirectional sum rate and at the same time eliminate the inter-user interference. We first develop two suboptimal transceivers which maximizes the uplink and downlink rates, respectively. Then a threshold to balance the uplink and downlink performance is proposed to achieve higher bidirectional sum rate. Simulation results show that our proposed transceiver scheme offers a higher bidirectional sum rate than the existing ZF and SA schemes.

II. System Model

We consider a multi-user TWR system, which consists of a BS equipped with N_B antennas, a RS equipped with N_R antennas and N_U single-antenna users, where $N_U \leq \min(N_B, N_R)$. The BS and the N_U users exchange downlink and uplink information via the RS. The bidirectional transmission takes place in two phases.

At the first phase, both the BS and the users transmit to the RS. The corresponding received signal at the RS is given by

$$\mathbf{y}_r = \mathbf{H}_{br}\beta_b\mathbf{W}_{bt}\mathbf{x}_b + \mathbf{H}_{ur}\mathbf{x}_u + \mathbf{n}_r, \quad (1)$$

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where $\mathbf{H}_{br} \in \mathbb{C}^{N_R \times N_B}$ is the channel matrix from the BS to the RS. $\mathbf{H}_{ur} = [\mathbf{h}_{1r}, \cdots, \mathbf{h}_{N_U r}]$, where $\mathbf{h}_{ir} \in \mathbb{C}^{N_R \times 1}$ is the channel vector from the ith user to the RS. $\mathbf{W}_{bt} \in \mathbb{C}^{N_B \times N_U}$ is the precoder at BS. β_b is chosen to guarantee the BS power constraint. $\mathbf{x}_b, \mathbf{x}_u$ are downlink and uplink signal vectors of the N_U users, respectively. $\mathbf{n}_r$ is the noise vector at the RS.

At the second phase, the RS precodes its received signals and broadcasts them to the BS and users. The received signals at the BS and the ith user are given by

$$\mathbf{y}_b = \mathbf{W}_{br}^T(\mathbf{H}_{br}^T \beta_r \mathbf{W}_r \mathbf{y}_r + \mathbf{n}_b), \quad (2)$$

$$y_{ui} = \mathbf{h}_{ir}^T \beta_r \mathbf{W}_r \mathbf{y}_r + n_{ui}, \quad (1 \le i \le N_U), \quad (3)$$

where $(\cdot)^T$ denotes the transpose of a matrix. $\mathbf{W}_r \in \mathbb{C}^{N_R \times N_R}$ is the weighting matrix at the RS, β_r is used to guarantee the RS power constraint. $\mathbf{W}_{br} \in \mathbb{C}^{N_B \times N_U}$ is the receive weighting matrix at the BS. $\mathbf{n}_b$ and n_{ui} are the noise signals at the BS and the ith user, respectively.

We assume that the transmitted signals of the BS and users have unit average power, $E(\mathbf{x}_b \mathbf{x}_b^H) = \mathbf{I}$, $E(\mathbf{x}_u \mathbf{x}_u^H) = \mathbf{I}$, and all the noise signals subject to complex Gaussian distribution with zero mean and N_0 variance, $\mathcal{CN}(0, N_0\mathbf{I})$. We also assume that all the channel matrices are known at the BS and the RS.

III. Problem Formulation

In this section, we formulate the system bidirectional sum rate maximization problem. First, we derive the constraints for the BS and RS transceivers to eliminate the inter-user interference. Substituting (1) into (2) and (3), the received signals at the BS and the ith user can be rewritten as

$$\mathbf{y}_b = \beta_r \beta_b \mathbf{W}_{br}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{H}_{br} \mathbf{W}_{bt} \mathbf{x}_b + \beta_r \mathbf{W}_{br}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{H}_{ur} \mathbf{x}_u + \beta_r \mathbf{W}_{br}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{n}_r + \mathbf{W}_{br}^T \mathbf{n}_b, \quad (4)$$

$$y_{ui} = \beta_r \beta_b \mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{H}_{br} \mathbf{W}_{bt} \mathbf{x}_b + \beta_r \mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{H}_{ur} \mathbf{x}_u + \beta_r \mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{n}_r + n_{ui} \quad (1 \le i \le N_U). \quad (5)$$

In the BS's received signal in (4), the first term is its transmitted signal in the first phase and thus can be removed. The second term is the desired uplink signal. The last two terms are the noise amplified by the RS and the noise at the BS receiver, respectively. To eliminate the interference among the N_U uplink signals, the following constraint should be satisfied,

$$\mathbf{w}_{bri}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{h}_{jr} = 0, \quad i \ne j, \quad (6)$$

where $\mathbf{w}_{bri}$ is the ith column of $\mathbf{W}_{br}$.

In the ith user's received signal, the first term consists of the downlink signals for all N_U users, the second term consists of the N_U users' transmitted signals in the first phase, and the last two terms are noise. Since there is no cooperation among users, the uplink and dowlink signals of other users are interference for the ith user. The transceivers should satisfy the following constraints to eliminate the inter-user interference,

$$\mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{H}_{br} \mathbf{w}_{btj} = 0, \quad i \ne j, \quad (7)$$

$$\mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{h}_{jr} = 0, \quad i \ne j, \quad (8)$$

where $\mathbf{w}_{btj}$ is the jth column of $\mathbf{W}_{bt}$.

Now we derive the system uplink and downlink rate. In the BS's received signal in (4), we have shown that the first term is its transmitted signal and thus can be removed. In the second term, $\mathbf{W}_{br}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{H}_{ur}$ is a diagonal matrix according to the constraint (6). Then the uplink rate can be calculated as,

$$R_u = \frac{1}{2} \sum_{i=1}^{N_u} \log_2 \left(1 + \frac{|\beta_r \mathbf{w}_{bri}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{h}_{ir}|^2 / N_0}{\|\beta_r \mathbf{w}_{bri}^T \mathbf{H}_{br}^T \mathbf{W}_r\|^2 + \|\mathbf{w}_{bri}^T\|^2}\right). \quad (9)$$

where the pre-log factor $1/2$ is due to the two phases transmission. Similarly, the downlink rate is given as

$$R_d = \frac{1}{2} \sum_{i=1}^{N_u} \log_2 \left(1 + \frac{|\beta_r \beta_b \mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{H}_{br} \mathbf{w}_{bti}|^2 / N_0}{\|\beta_r \mathbf{h}_{ir}^T \mathbf{W}_r\|^2 + 1}\right), \quad (10)$$

Then the sum rate optimization problem is formulated as

$$\underset{\mathbf{W}_r, \mathbf{W}_{bt}, \mathbf{W}_{br}}{\text{Max.}} \quad R_u + R_d \quad (11a)$$

$$\text{s.t.} \quad \mathbf{w}_{bri}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{h}_{jr} = 0, \quad i \ne j \quad (11b)$$

$$\mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{H}_{br} \mathbf{w}_{btj} = 0, \quad i \ne j \quad (11c)$$

$$\mathbf{h}_{ir}^T \mathbf{W}_r \mathbf{h}_{jr} = 0, \quad i \ne j \quad (11d)$$

$$\|\beta_b \mathbf{W}_{bt}\|^2 = P_B, \quad (11e)$$

$$\|\beta_r \mathbf{W}_r \mathbf{y}_r\|^2 = P_R, \quad (11f)$$

where P_B and P_R are the transmit power of the BS and RS, respectively.

IV. BS and RS Transceiver Design

By solving the problem (11), we will obtain the optimal BS and RS weighting matrices. However, it is difficult to solve this non-convex joint optimization problem. In this section, we propose a heuristic solution for the BS and RS weighting matrices aiming to maximize the system sum rate.

First we design the BS weighting matrices. In the BS's received signal in (4), we have presented that the first term is the BS's transmitted signals and can be removed. In the case that if the the RS-forward noise term can be neglected[1], then the BS's received signal can be rewritten as

$$\mathbf{y}_b = \beta_r \mathbf{W}_{br}^T \mathbf{H}_{br}^T \mathbf{W}_r \mathbf{H}_{ur} \mathbf{x}_u + \mathbf{W}_{br}^T \mathbf{n}_b.$$

In that case, the optimal BS receiver under the constraint (6) is a ZF receiver as follows,

$$\mathbf{W}_{br} = ((\mathbf{H}_{br}^T \mathbf{W}_r \mathbf{H}_{ur})^\dagger)^T, \quad (12)$$

Similarly, if the RS-forward noise term can be neglected at each user, the optimal BS transmitter under the constraint (7) is a ZF precoder,

$$\mathbf{W}_{bt} = (\mathbf{H}_{ur}^T \mathbf{W}_r \mathbf{H}_{br})^\dagger \mathbf{G}_b \quad (13)$$

where $\mathbf{G}_b$ is the BS power allocation matrix. In this paper, we simply use the equal power allocation for each user. Under this assumption and the BS power constraint in (11e), we have $\beta_b^2 \|\mathbf{w}_{btj}\|^2 = P_B/N_U$.

[1]This case may happen, e,g., the signal-to-noise-ratio (SNR) is high when the BS and users transmit to the RS in the first phase

We take the above ZF transceiver as a heuristic solution for the BS weighting matrices, and then design the RS weighting matrix. It is difficult to design a RS weighting matrix to maximize the bidirectional sum rate. Therefore, we intuitively change our objective to design two RS weighting matrices $\mathbf{W}_r^U$ and $\mathbf{W}_r^D$, which respectively maximize the uplink rate and downlink rate. Then we add $\mathbf{W}_r^U$ and $\mathbf{W}_r^D$ together as our final solution of the RS weighting matrix. In the following, we will respectively solve $\mathbf{W}_r^U$ and $\mathbf{W}_r^D$.

A. Transceiver optimization for downlink

In this subsection, we design $\mathbf{W}_r^D$ to maximize the downlink rate. The optimization objective is R_d in (10). Among the three non-interference constraints (11b), (11c) and (11d), the first two has been satisfied by adopting the $\mathbf{W}_{br}$ and $\mathbf{W}_{bt}$ in (12) and (13), therefore, we will not list them in the downlink rate maximization problem. Since we are optimizing the downlink rate, we assume that the users do not transmit, then the RS's received signal in the first phase is rewritten as

$$\tilde{\mathbf{y}}_r = \mathbf{H}_{br}\beta_b\mathbf{W}_{bt}\mathbf{x}_b + \mathbf{n}_r.$$

Further, the RS power constraint in (11f) is rewritten as $\|\beta_r\mathbf{W}_r\tilde{\mathbf{y}}_r\|^2 = P_R$. At last, we obtain the downlink rate maximization problem as

$$\operatorname*{Max.}_{\mathbf{W}_r^D}\ \frac{1}{2}\sum_{i=1}^{N_u}\log_2\left(1+\frac{|\beta_r\beta_b\mathbf{h}_{ir}^T\mathbf{W}_r^D\mathbf{H}_{br}\mathbf{w}_{bti}|^2}{(\|\beta_r\mathbf{h}_{ir}^T\mathbf{W}_r^D\|^2+1)N_0}\right) \quad (14a)$$

$$\text{s.t.}\ \ \mathbf{h}_{ir}^T\mathbf{W}_r^D\mathbf{h}_{jr} = 0,\quad i\neq j \quad (14b)$$

$$\|\beta_r\mathbf{W}_r^D\tilde{\mathbf{y}}_r\|^2 = P_R. \quad (14c)$$

First, we can show that the optimal $\mathbf{W}_r^D$ has the following structure (see Appendix)

$$\mathbf{W}_r^D = (\mathbf{H}_{ur}^T)^\dagger\mathbf{G}_r\mathbf{U}^T, \quad (15)$$

where $\mathbf{G}_r \in \mathbb{C}^{N_u\times N_u}$ is a diagonal matrix and each column of $\mathbf{U}\in\mathbb{C}^{N_r\times N_u}$ has unit norm, i.e., $\|\mathbf{u}_j\|^2 = 1$.

In this structure, $(\mathbf{H}_{ur}^T)^\dagger$ acts as a ZF precoder to broadcast the RS received signals to the users. $\mathbf{G}_r = \text{diag}(p_{r1},\cdots,p_{rN_u})$ denotes the power allocation for different streams of signals and $\mathbf{U}^T$ is the receiver to separate the N_U downlink signals from the BS.

Again we simply use the uniform power allocation at the RS. We denote each column of $(\mathbf{H}_{ur}^T)^\dagger$ as $\mathbf{q}_i$. Since each data stream is received by $\mathbf{u}_i^T$, amplified by p_{ri}, and then forwarded by $\mathbf{q}_i$, we calculate each p_{ri} to ensure that each $p_{ri}\mathbf{q}_i\mathbf{u}_i^T$ has the same norm, so that the RS uses equal power to process each data stream.

Now we focus on the design of the matrix $\mathbf{U}$. Substituting (15) into (14), we rewrite the optimization problem as

$$\operatorname*{Max.}_{\mathbf{U}}\ \frac{1}{2}\sum_{i=1}^{N_u}\log_2\left(1+\frac{\beta_r^2p_{ri}^2\beta_b^2|\mathbf{u}_i^T\mathbf{H}_{br}\mathbf{w}_{bti}|^2}{(\beta_r^2p_{ri}^2+1)N_0}\right)$$
$$\text{s.t.}\ \ \mathbf{u}_i^T\mathbf{h}_{jr} = 0,\quad i\neq j;\quad \|\mathbf{u}_i\| = 1;$$
$$\|\beta_r(\mathbf{H}_{ur}^T)^\dagger\mathbf{G}_r\mathbf{U}^T\tilde{\mathbf{y}}_r\|^2 = P_R. \quad (16)$$

As $\beta_r p_{ri}$ is a non-concave function of $\mathbf{U}$ due to the last constraint, it is still difficult to handle the above optimization problem. Therefore, we propose a suboptimal solution for it.

As we have explained that $\mathbf{U}^T$ in $\mathbf{W}_r$ is the receive weight at the RS for the BS-RS transmission. The sub-optimal solution is to design $\mathbf{U}$ to maximize the data rate in the BS-RS transmission instead of maximizing the downlink rate. The sub-optimal problem can be formulated as

$$\operatorname*{Max.}_{\mathbf{U}}\ \sum_{i=1}^{N_u}\log_2(1+\beta_b^2|\mathbf{u}_i^T\mathbf{H}_{br}\mathbf{w}_{bti}|^2/N_0)$$
$$\text{s.t.}\ \ \mathbf{u}_i^T\mathbf{h}_{jr} = 0,\quad i\neq j;\quad \|\mathbf{u}_i\| = 1. \quad (17)$$

Although now we optimize the data rate in the BS-RS transmission, we still have to restrict $\mathbf{U}$ to satisfy the constraints guaranteeing the non-interference bidirectional transmission.

We should notice that if the RS transmit power goes to infinity, then the last constraint in (16) can be omitted. In addition, the β_r will go to infinity, so the optimization objective function in (16) is the same as that in (17), except for the pre-log factor 1/2. Therefore, in that case, the problem in (17) is equivalent to the problem in (16).

Since we already determined that

$$\mathbf{W}_{bt} = (\mathbf{H}_{ur}^T\mathbf{W}_r^D\mathbf{H}_{br})^\dagger\mathbf{G}_b = (\mathbf{U}^T\mathbf{H}_{br})^\dagger\mathbf{G}_r^{-1}\mathbf{G}_b,$$

then $\mathbf{W}_{bt}$ is a pseudo inverse of $\mathbf{U}^T\mathbf{H}_{br}$ with power allocation. Using the principle of orthogonal projection, we know that $|\mathbf{u}_i^T\mathbf{H}_{br}\mathbf{w}_{bti}|/\|\mathbf{w}_{bti}\|$ is equal to the projection of $\mathbf{u}_i^T\mathbf{H}_{br}$ on the orthogonal subspace of $\overline{\mathbf{U}}_i^T\mathbf{H}_{br}$, where $\overline{\mathbf{U}}_i$ is the matrix $\mathbf{U}$ with the ith column $\mathbf{u}_i$ being removed. Therefore, we have

$$\beta_b^2|\mathbf{u}_i^T\mathbf{H}_{br}\mathbf{w}_{bti}|^2 = (\beta_b^2\|\mathbf{w}_{bti}\|^2)(|\mathbf{u}_i^T\mathbf{H}_{br}\mathbf{w}_{bti}|^2/\|\mathbf{w}_{bti}\|^2)$$
$$=(P_B/N_U)|\mathbf{u}_i^T\mathbf{H}_{br}S_\perp(\overline{\mathbf{U}}_i^T\mathbf{H}_{br})|^2, \quad (18)$$

where we use the BS equal power allocation assumption that $\beta_b^2\|\mathbf{w}_{bti}\|^2 = P_B/N_U$. $S_\perp(\mathbf{X})$ denotes the subspace orthogonal to a matrix $\mathbf{X}$, which is given by,

$$S_\perp(\mathbf{X}) = \mathbf{I}-\mathbf{X}^H(\mathbf{X}\mathbf{X}^H)^{-1}\mathbf{X}$$

From (18), we can see that our task is to find $\mathbf{U}$ to maximize the projection $|\mathbf{u}_i^T\mathbf{H}_{br}S_\perp(\overline{\mathbf{U}}_i^T\mathbf{H}_{br})|$ under the constraint in (17) that $\mathbf{u}_i \in S_\perp(\overline{\mathbf{H}}_{ir})$, $\|\mathbf{u}_i\| = 1$, where $\overline{\mathbf{H}}_{ir}$ is the channel matrix $\mathbf{H}_{ur}$ with the ith column $\mathbf{h}_{ir}$ being removed.

Here we apply the following procedure to solve this problem. We calculate the N_u columns of $\mathbf{U}$ in N_u iterations. In the kth iteration, there are $k-1$ columns of $\mathbf{U}$ which have been found. We denote I_d as the set of the indexes of the already found columns. Let $\mathbf{V}$ denote the subspace spanned by these already determined vectors $\mathbf{u}_i^T\mathbf{H}_{br}$, $i \in I_d$. Our task in the kth iteration is to find the $\mathbf{u}_i, i \notin I_d$ satisfying $\mathbf{u}_i \in S_\perp(\overline{\mathbf{H}}_{ir}), \|\mathbf{u}_i\| = 1$ and maximizing the projection $\mathbf{u}_i^T\mathbf{H}_{br}S_\perp(\mathbf{V})$. The detailed procedure is presented in Table I.

We use $\mathbf{U}^\star$ to denote the optimized result for $\mathbf{U}$. Then the transceiver designed for downlink can be given by

$$\mathbf{W}_r^D = (\mathbf{H}_{ur}^T)^\dagger\mathbf{G}_r\mathbf{U}^{\star T} \quad (19)$$

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TABLE I
CALCULATING THE MATRIX $\mathbf{U}$

step 1:	initialize $\mathbf{V}$ as an empty matrix, let $T = \{1, 2, \cdots, N_u\}$
step 2:	find $i^\star = \text{argmax}(\lambda_{max}(S_\perp(\overline{\mathbf{H}}_{ir})\mathbf{H}_{br}S_\perp(\mathbf{V})))$, $i \in T$
step 3:	perform singular value decomposition of $S_\perp(\overline{\mathbf{H}}_{i^\star r})\mathbf{H}_{br}S_\perp(\mathbf{V})$
step 4:	let $\mathbf{u}_{i^\star}$ be the left singular vector corresponding to λ_{max} of $S_\perp(\overline{\mathbf{H}}_{i^\star r})\mathbf{H}_{br}S_\perp(\mathbf{V})$, while let $\mathbf{v}$ be the right singular vector corresponding to λ_{max}. Then let $\mathbf{V} = [\mathbf{V}; \mathbf{v}]$
step 5:	remove $i^\star$ from T. If T is not empty, go back to step 2, otherwise, the loop ends.

In the first iteration, as $\mathbf{V}$ is an empty matrix, we define $S_\perp(\mathbf{V}) = \mathbf{I}$. $\lambda_{max}(\cdot)$ means the maximum singular value of a matrix.

B. Transceiver optimization for uplink

Using a similar method as that in the last subsection, we divide the $\mathbf{W}_r^U$ into three parts, i.e., a receive weighting matrix for the user-RS transmission, a power allocation matrix, and a precoder matrix for the RS-BS transmission. We then optimize the receive and precoder weighting matrix separately and obtain the following suboptimal $\mathbf{W}_r^U$ for uplink,

$$\mathbf{W}_r^U = \mathbf{U}^\star \mathbf{G}_r \mathbf{H}_{ur}^\dagger \quad (20)$$

Detailed derivation is not presented due to the lack of space.

C. Balancing the uplink and downlink for higher bidirectional sum rate

The two weighting matrices $\mathbf{W}_r^U$ and $\mathbf{W}_r^D$ are derived to maximize the uplink and downlink rates, respectively. In this subsection, we make a balance between the uplink and downlink rates to achieve higher bidirectional sum rate. We let the RS allocate a fraction of its power to $\mathbf{W}_r^U$ and the rest of its power to $\mathbf{W}_r^D$. We use a threshold to control the power proportion of the two parts. The RS weighting matrix can be expressed as

$$\mathbf{W}_r^{BL} = \gamma \mathbf{W}_r^U + (1-\gamma)\mathbf{W}_r^D, \quad (21)$$

where $0 \leq \gamma \leq 1$. For different values of γ, we choose proper β_r to guarantee the total transmit power of the RS. As γ varies between 0 and 1, the RS adjusts its power allocated to the $\mathbf{W}_r^U$ and $\mathbf{W}_r^D$ to balance the uplink and downlink performance. In next section, we will show through simulation that by choosing proper γ, the system can achieve higher bidirectional sum rate than the existing ZF and SA schemes.

V. SIMULATION RESULTS

In this section, we compare the sum rate of different transceiver schemes by simulations. We assume all the channels are independent identically distributed Rayleigh fading channels. For the fairness of comparison, we use equal power allocation in all the transceiver schemes. We assume that the noise variance N_0 is identical at the BS, RS and each user. The transmit power of each user is normalized as 1. The BS and RS transmit power normalized by single user's transmit power are denoted as P_B and P_R, respectively. We define $1/N_0$ as the transmit signal-to-noise ratio (SNR). All the simulation results are averaged over 500 Monte-carlo tests of channels.

A. Balancing between the uplink and downlink rates

In this subsection, we investigate the balancing between the uplink and downlink rates using the proposed algorithm by changing the threshold value. We fix the antenna number at the BS, RS and the number of the users as 2, 4 and 2, respectively. We set the normalized transmit power of the BS and RS as 2 and 4, respectively. The transmit SNR is 30dB. In Fig. 1, the upper sub-figure shows the balance between the uplink and downlink rates versus the threshold γ, while the lower sub-figure shows the bidirectional sum rate versus γ.

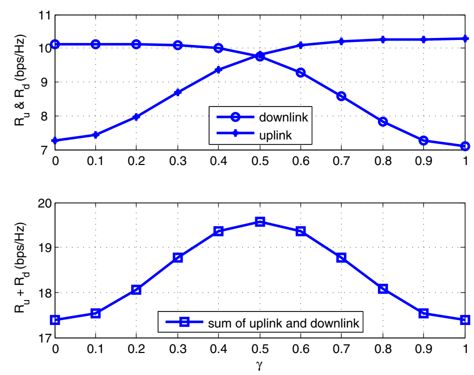

Fig. 1. Balance between uplink and downlink Rates

When $\gamma = 0$ or 1, the transceivers degenerate into the downlink or uplink suboptimal schemes. We can see that the downink suboptimal transceiver scheme has high downlink rate but low uplink rate. The bidirectional sum rate therefore is low. Similar phenomena can be seen on the uplink suboptimal transceiver scheme. As the γ changes from 0 to 1, the uplink and downlink rates vary and higher bidirectional sum rate can be achieved. We can see that when $\gamma = 0.5$, the system has the highest bidirectional sum rate. In the following simulation, we will always set $\gamma = 0.5$ in our proposed algorithm.

B. Comparison among different transceiver schemes

In this subsection, we compare the uplink, downlink and bidirectional sum rates of our proposed schemes and the existing ZF and SA scheme. We set the BS antenna number and the user number as $N_B = N_U = 2$. The normalized transmit power of BS and RS is fixed as $P_B = 2$, $P_R = 4$, respectively. The transmit SNR is 30dB. We change the RS antenna number and simulate the sum rate of all the schemes, respectively. The uplink and downlink rates comparison results are shown in Fig. 2, while the bidirectional sum rate comparison is shown in Fig. 3.

First we compare the existing SA and ZF schemes. We see that the SA scheme is better when the RS antenna number is small while the ZF scheme outperforms the SA scheme when the RS antenna number is large. In addition, we note that when the RS antenna number is less than 4, the downlink rate of the ZF scheme decreases sharply, as the RS does not have enough antennas to cancel all the interference for each user.

The proposed uplink suboptimal transceiver scheme achieves highest uplink rate in all the schemes, while its

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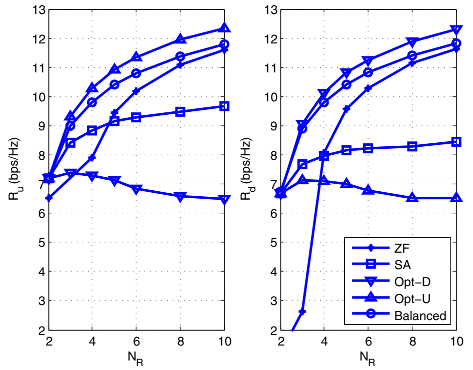

Fig. 2. Comparison on the uplink and downlink rates

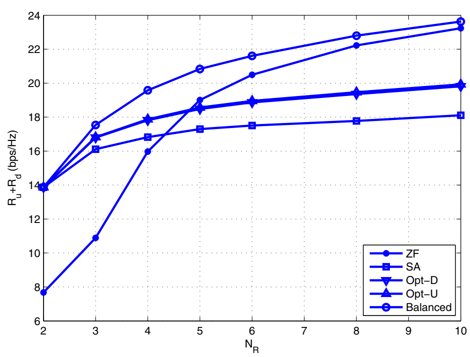

Fig. 3. Comparison on the bidirectional sum rate

downlink performance is poor. Similar results can be seen on the downlink suboptimal scheme.

The proposed balanced algorithm achieves high uplink and downlink rates simultaneously. Its bidirectional, uplink and downlink sum rates are higher than those of the existing schemes regardless of the number of antennas at the RS.

Due to the lack of space, we do not provide the extensive results, which show that our proposed transceiver scheme outperforms the existing schemes at high or low transmit SNR, at various BS antenna numbers and scheduled user numbers.

VI. Conclusion

In this paper, we designed the transceiver structure for multi-user multi-antenna TWR systems, aiming at maximizing the bidirectional sum rate under the constraint of no inter-user interference. Sub-optimal solutions maximizing the uplink and downlink rates are derived, respectively. We also proposed an algorithm to balance the uplink and downlink rates to further improve the bidirectional sum rate. Simulation results showed that the proposed transceiver scheme achieves higher uplink, downlink and bidirectional sum rates than existing schemes.

Appendix

Proof of the Optimal Structure of $\mathbf{W}_r^D$ for Downlink in (15)

Without loss of generality, we can write $\mathbf{W}_r^D$ as

$$\mathbf{W}_r^D = [\mathbf{V}_{ur}\ \mathbf{V}_{ur}^{\perp}][\mathbf{A}\ \mathbf{B}]^T = \mathbf{V}_{ur}\mathbf{A}^T + \mathbf{V}_{ur}^{\perp}\mathbf{B}^T, \quad (22)$$

where $\mathbf{A}, \mathbf{B}$ are two arbitrary matrices. $\mathbf{V}_{ur}$ consists of the N_u singular vectors of $\mathbf{H}_{ur}^T$, while $\mathbf{V}_{ur}^{\perp}$ consists of the $N_r - N_u$ singular vectors of the orthogonal subspace of $\mathbf{H}_{ur}^T$.

As $\mathbf{h}_{ir}^T\mathbf{V}_{ur}^{\perp} = \mathbf{0}$, R_d in (14a) can be rewritten as

$$R_d = \frac{1}{2}\sum_{i=1}^{N_u}\log_2\left(1 + \frac{|\beta_b \mathbf{h}_{ir}^T\mathbf{V}_{ur}\mathbf{A}^T\mathbf{H}_{br}\mathbf{w}_{bti}|^2}{(\|\mathbf{h}_{ir}^T\mathbf{V}_{ur}\mathbf{A}^T\|^2 + 1/\beta_r^2)N_0}\right). \quad (23)$$

We will prove that R_d will be maximized when $\mathbf{B} = \mathbf{0}$.

First, we show that $\mathbf{w}_{bti}$ is not a function of $\mathbf{B}$. As we have

$$\mathbf{W}_{bt}^T = (\mathbf{H}_{ur}^T\mathbf{W}_r^D\mathbf{H}_{br})^{\dagger}\mathbf{G}_b = (\mathbf{H}_{ur}^T\mathbf{V}_{ur}\mathbf{A}^T\mathbf{H}_{br})^{\dagger}\mathbf{G}_b,$$

then each column of it, $\mathbf{w}_{bti}$, is not a function of $\mathbf{B}$.

Since β_b only depends on the BS power and $\mathbf{W}_{bt}$, it is not a function of $\mathbf{B}$, neither.

Second, we show that $1/\beta_r^2$ is minimized when $\mathbf{B} = \mathbf{0}$. From the RS power constraint in (14c), we obtain $1/\beta_r^2$ as

$$1/\beta_r^2 = \|\mathbf{W}_r^D\tilde{\mathbf{y}}_r\|^2/P_R = (\|\mathbf{V}_{ur}\mathbf{A}^T\tilde{\mathbf{y}}_r + \mathbf{V}_{ur}^{\perp}\mathbf{B}^T\tilde{\mathbf{y}}_r\|^2)/P_R$$
$$= (\|\mathbf{V}_{ur}\mathbf{A}^T\tilde{\mathbf{y}}_r\|^2 + \|\mathbf{V}_{ur}^{\perp}\mathbf{B}^T\tilde{\mathbf{y}}_r\|^2)/P_R \geq \|\mathbf{V}_{ur}\mathbf{A}^T\tilde{\mathbf{y}}_r\|^2/P_R.$$

From (23), we can see that since β_b and $\mathbf{w}_{bti}$ are not functions of $\mathbf{B}$, and $1/\beta_r^2$ is minimized when $\mathbf{B} = \mathbf{0}$, R_d is maximized when $\mathbf{B} = \mathbf{0}$. Therefore, the optimal $\mathbf{W}_r^D$ should be $\mathbf{W}_r^D = \mathbf{V}_{ur}\mathbf{A}^T$. Assume that the singular value decomposition of $\mathbf{H}_{ur}^T$ is expressed as $\mathbf{U}_{ur}\mathbf{D}_{ur}\mathbf{V}_{ur}^H$, where $\mathbf{D}_{ur}, \mathbf{U}_{ur} \in \mathbb{C}^{N_u \times N_u}$ are non-singular matrices, then we have

$$\mathbf{W}_r^D = \mathbf{V}_{ur}\mathbf{A}^T = \mathbf{V}_{ur}(\mathbf{D}_{ur}^{-1}\mathbf{U}_{ur}^H\mathbf{U}_{ur}\mathbf{D}_{ur})\mathbf{A}^T$$
$$= (\mathbf{H}_{ur}^T)^{\dagger}\mathbf{U}_{ur}\mathbf{D}_{ur}\mathbf{A}^T \triangleq (\mathbf{H}_{ur}^T)^{\dagger}\mathbf{M}^T.$$

We divide the matrix $\mathbf{M} = [\mathbf{m}_1, \cdots, \mathbf{m}_{N_u}]$ into two matrices, $\mathbf{U} = [\mathbf{u}_1, \cdots, \mathbf{u}_{N_u}]$ and $\mathbf{G}_r = \mathrm{diag}([p_{r1}, \cdots, p_{rN_u}])$, where $\mathbf{u}_j = \mathbf{m}_j/\|\mathbf{m}_j\|$ and $p_{rj} = \|\mathbf{m}_j\|$. Finally, we have

$$\mathbf{W}_r^D = (\mathbf{H}_{ur}^T)^{\dagger}\mathbf{M}^T = (\mathbf{H}_{ur}^T)^{\dagger}\mathbf{G}_r\mathbf{U}^T,$$

as shown in (15).

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