Transceiver Design for Hybrid One-Way and Two-Way Relay Networks

Miao Wang, Student Member, IEEE, Peng Wang, Member, IEEE, Yonghui Li, Senior Member, IEEE, Zhangdui Zhong, Fanggang Wang, Member, IEEE, and Branka Vucetic, Fellow, IEEE

Abstract—Due to a variety of service types required by different users, unidirectional and bidirectional data transmissions may coexist in a relay network. In this letter, we consider such a hybrid one-way and two-way relay network, where both unidirectional and bidirectional data transmissions are delivered simultaneously between different user pairs via a common multi-antenna relay node. We first develop a relaying scheme that provides inter-pair interference free transmissions for all users. A near optimal power allocation method at the relay is then proposed to maximize the system sum rate. Numerical results show that our relaying scheme significantly outperforms the traditional zero-forcing based scheme.

Index Terms—Hybrid relay network, multi-antenna, power allocation.

I. INTRODUCTION

R

ELAY transmission has received considerable attention due to its capability of coverage extension, rate increase and reliability enhancement for wireless networks [1]–[4]. Various transmission strategies have been proposed in [4], [5] for single-user one-way relay networks, where a relay node is used to help the data transmission from a source to a destination. For relay networks with multiple source-destination pairs, multiple antennas are equipped at the relay to combat interference among different users. The corresponding precoding design at the relay node has been discussed in [6].

When the aforementioned schemes are applied in two-way relay networks, it requires four phases to accomplish a bi-directional transmission between a pair of users via the relay node. To improve the spectral efficiency, digital or analogue network coding has been incorporated such that a two-way relay transmission could be realized in three [7] or even two phases [8]. For multi-pair two-way relay networks, the network coded relay design has also been investigated thoroughly [9]–[11]. However, most existing research efforts have only focused on pure one-way or two-way relaying. In a wireless network, different types of services, including unidirectional traffics (e.g., file downloading and emails) and bidirectional traffics (e.g., online games and traditional voice conversations), may coexist. Even for a bidirectional relay network, pure two-way relaying may not be the best choice to maximize the system sum rate, as will be demonstrated in this paper. Thus it is worth investigating the schemes that are applicable to hybrid one-way and two-way relay networks.

Power allocation in relay networks is an important approach for performance enhancement. In [12], the authors formulated the power allocation problem for throughput maximization of a cellular relay network into a convex problem. However, the convex formulation cannot be applied to a multi-pair relay network as users cannot transmit or receive cooperatively. In [11], [13], the authors discussed the power allocation to maximize the instantaneous SNR of the worst user in a two-way relay network. To tackle the resulting non-convex problem, [13] proposed a complicated method by first converting the optimization problem into a quadratically constrained quadratic program (QCQP) and then utilizing semidefinite relaxation to obtain a suboptimal solution to the QCQP. In [11], the non-convex problem is approximated to a convex one by discarding the non-diagonal elements in the power constraint at the relay. However, through the approximation, the newly obtained feasible region may not contain all the feasible solutions to the original problem. In addition, it is unclear how the system sum rate is affected by power allocation.

In this letter, we consider a hybrid relay network where both one-way and two-way data transmissions are accomplished simultaneously via a common relay. We first propose an inter-pair interference free transmission scheme for the network and then discuss the power allocation at the relay to maximize the system sum rate. Numerical results show that our scheme significantly outperforms the conventional zero-forcing relaying.

II. SYSTEM MODEL

Consider a wireless network consisting of an $N$-antenna relay node and $K+L$ pairs of single-antenna users $\{U_{m,1}, U_{m,2}\}_{m=1}^{K+L}$. For the first $K$ user pairs, bidirectional information exchanges are required between each pair, while for the last $L$ user pairs, only the information delivery from $U_{m,1}$ to $U_{m,2}$ ($m = K+1, \ldots, K+L$) is required. We assume no direct link between each user pair. In each transmission block, all the sources first transmit simultaneously to the relay. The length-$N$ signal vector received at the relay can be expressed as

$$y = \sum_{m=1}^{K+L} (h_{m,1}x_{m,1} + h_{m,2}x_{m,2}) + \sum_{m=K+1}^{K+L} h_{m,1}x_{m,1} + n_B$$

(1)
where $\bfh_{m,i} \in \mathbb{C}^{N \times 1}$ ($i = 1, 2$) is the channel vector from user $U_{m,i}$ to the relay, $\bfm_{m,i}$ is the corresponding transmitted signal with a fixed and normalized power level $F[\|\bfm_{m,i}\|^2 = 1$, and $\bfu_R \in \mathbb{C}^{N \times 1}$ is the noise vector at the relay following an independent and identical complex Gaussian distribution, i.e., $\bfu_R \sim \mathcal{CN} (0, \sigma_u^2 I_N)$. After receiving the signals from the sources, the relay precodes its received signal with a matrix $\bfW \in \mathbb{C}^{N \times N}$, yielding

$$\bfx_R = \bfW \bfy_R.$$  \hspace{1cm} (2)

The precoded signal $\bfx_R$ is then broadcast to the destinations subject to a power constraint $P_R$, i.e.,

$$F[\|\bfx_R\|^2] \leq P_R.$$  \hspace{1cm} (3)

The received signal at user $U_{m,i}$ is given by

$$\bfm_{m,i} = \bfh_{m,i}^\top \bfx_R + n_{m,i},$$  \hspace{1cm} (4)

where $\bfh_{m,i} \in \mathbb{C}^{N \times 1}$ is the downlink channel vector of $U_{m,i}$, and $n_{m,i}$ is the noise following $\mathcal{CN}(0, \sigma_n^2)$.

### III. DESIGN OF RELAY PRECODING MATRIX

In this section, we propose a relaying scheme for the hybrid relay network to guarantee inter-pair interference free transmissions. The whole precoding matrix $\bfW$ at the relay can be designed as

$$\bfW = \sum_{m=1}^{N+1} c_m \bfW_m,$$  \hspace{1cm} (5)

where $c_m$ is a weight factor that is related to each pair's allocated power at the relay and will be detailed later in Section IV, and $\bfW_m$ is the precoding matrix for the $m$-th user pair that can be further decomposed as

$$\bfW_m = \bfQ_m \bfS_m \bfF_m.$$  \hspace{1cm} (6)

In (6), the matrix $\bfF_m$ is used to collect the signal(s) for the $m$-th user pair and at the same time cancel the interference from the other users, $\bfQ_m$ is the corresponding forwarding matrix for eliminating the interference to the other pairs.

We first consider the design of $\bfF_m$. Define

$$\bfH_m = \begin{bmatrix} \bfh_{m,1} & \bfh_{m,2} \\ \vdots & \vdots \\ \bfh_{m,K} & \bfh_{m,K+1} \end{bmatrix},$$

and $\bfH_m = \begin{bmatrix} \bfh_{m,1} & \bfh_{m,2} & \cdots & \bfh_{m,K+1} \end{bmatrix}$. To avoid interference from the other user pairs, $\bfF_m$ should lie in the null space of $\bfH_m$. The latter can be obtained through the SVD of $\bfH_m$, i.e.,

$$\bfH_m = \Sigma \bfU_m \bfH_m,$$  \hspace{1cm} (7)

where $\bfU_m \Sigma \bfH_m$ and $\bfU_m$ contain the left singular vectors of $\bfH_m$ that correspond to non-zero and zero singular values, respectively. Thus we have

$$\bfF_m = (\bfU_m \Sigma \bfH_m)^H.$$  \hspace{1cm} (8)

Similarly, to design $\bfQ_m$, let us define

$$\bfG_m = \begin{bmatrix} \bfg_{m,1} & \bfg_{m,2} \\ \vdots & \vdots \\ \bfg_{m,K} & \bfg_{m,K+1} \end{bmatrix},$$

and $\bfG_m = \begin{bmatrix} \bfg_{m,1} & \bfg_{m,2} & \cdots & \bfg_{m,K+1} \end{bmatrix}$. The SVD of $\bfG_m$ is given by

$$\bfG_m = \bfU_m \bf\Sigma_m \bf\Sigma_m^H.$$  \hspace{1cm} (9)

where $\bf\Sigma_m$ and $\bf\Sigma_m^H$ contain the right singular vectors of $\bfG_m$ that correspond to non-zero and zero singular values, respectively. To avoid the interference to the other user pairs, the matrix $\bfQ_m$ should be designed as

$$\bfQ_m = \bfV_m \bf\Sigma_m \bfH_m.$$  \hspace{1cm} (10)

Finally, we discuss the design of $\bfS_m$. For convenience, we write the signal(s) received at the $m$-th pair as a vector, i.e.,

$$\bfm_m = \begin{bmatrix} \bfm_{m,1} \\ \bfm_{m,2} \\ \vdots \\ \bfm_{m,K+1} \end{bmatrix},$$  \hspace{1cm} (11)

where $\bfm_m$ is the corresponding forwarding matrix for eliminating the interference to the other user pairs.

Note that in the above precoder design, $\bfF_m$ and $\bfQ_m$ are a $(N \times K+1, K+1)$-by-$N$ or $N$-by-$(N \times K+1, K+1)$-by-$N$ matrix for one-way relaying pairs and $(N \times K+2, K+1)$-by-$N$ or $N$-by-$(N \times K+2, K+1)$-by-$N$ matrix for two-way relaying pairs. Correspondingly, $\bfS_m$ is a $(N \times K+1, K+1)$-dimension square matrix for one-way relaying pairs and $(N \times K+2, K+1)$-dimension square matrix for two-way relaying pairs. Thus to guarantee the existence of the matrices $\bfF_m$, $\bfQ_m$ and $\bfS_m$, the following inequation should be satisfied.

$$N \geq \begin{bmatrix} 2K + L_1, & L \neq 0; \\ 2K + 1, & L = 0 \end{bmatrix}$$  \hspace{1cm} (13)

When $L = 0$, the model reduces to a two-way relay network, and our transceiver design is the same as the coherent combining of null-space vectors scheme in [9]. When $K = 0$, the model reduces to one-way relaying, and the transceiver design is the conventional zero-forcing relaying.

### IV. POWER ALLOCATION OPTIMIZATION

#### A. Problem Formulation

Our objective in this section is to maximize the system sum rate under power constraint $P_R$ at the relay. The formulation of the objective function is as follows. Based on the precoding matrix designed in Section III and after pre-cancelation of self-interference at user $U_{m,i}$, the received signal is

$$\bfm_{m,i} = c_{m,k_{m,i}} \bfW_m \bfh_{m,i} \bfm_{m,i+1} + c_{m,k_{m,i}} \bfW_m \bfu_R + n_{m,i},$$  \hspace{1cm} (14)

The corresponding received SNR at $U_{m,i}$ can be calculated as

$$\text{SNR}_{m,i} = \frac{c_{m,k_{m,i}} \bfW_m \bfh_{m,i} \bfm_{m,i+1}^2}{c_{m,k_{m,i}} \bfW_m \bfh_{m,i} \bfm_{m,i+1}^2 \sigma_u^2 + \sigma_n^2}.$$  \hspace{1cm} (15)
Accordingly, the total sum rate is given by
\[
R = \sum_{m=1}^{K} \frac{1}{2} \log(1 + S\mathbb{N}_{m,1}) + \sum_{m=1}^{K+L} \frac{1}{2} \log(1 + S\mathbb{N}_{m,2}).
\] (16)

To formulate the power constraint at the relay, we substitute (1) and (5) into (2) and rewrite \(x_R\) as
\[
x_R = \sum_{m=1}^{K} c_m W_m (h_{m,1} x_{m,1} + h_{m,2} x_{m,2}) + \sum_{m=K+1}^{K+L} c_m W_m x_{m,1} + W_R.
\] (17)

In (17), the transmit power for the signal from user \(U_m,1\) can be calculated as
\[
E\|c_m W_m h_{m,1} x_{m,1}\|^2 = c_m^T \text{Tr} \{W_m^H W_m h_{m,1} h_{m,1}^H\} = c_m^T d_m. \tag{18}
\]

where \(d_m = \text{Tr} \{W_m^H W_m h_{m,1} h_{m,1}^H\}\). Then the total transmit power for signals from all users in (17), is given by
\[
\sum_{m=1}^{K+L} c_m^T (d_m,1 + d_m,2) + \sum_{m=K+1}^{K+L} c_m^T d_{m,1} = c^T D c \tag{19}
\]

where \(c = [c_1, \ldots, c_{K+L}]^T\) and \(D\) is a \((K + L) \times (K + L)\) diagonal matrix with the first \(K\) diagonal entries being \(d_{m,1} + d_{m,2}\) \((m = 1, \ldots, K)\) and the last \(L\) diagonal entries being \(d_{m,1}\) \((m = K + 1, \ldots, K + L)\). Similarly, the corresponding noise power contained in \(x_R\) can be calculated as
\[
E\|W_R x_R\|^2 = \sigma^2_{\text{NR}} \text{Tr} \left\{ \sum_{i=1}^{K+L} \sum_{j=1}^{K+L} c_i c_j W_i^H W_j \right\} = c^T \Psi c \tag{20}
\]

where \(\Psi = [\psi_{i,j}]\) is a \(K \times K\) full matrix with \(\psi_{i,j} = \sigma^2_{\text{NR}} \text{Tr} \{W_i^H W_j\}\). Recalling the power constraint (3) at the relay, we have
\[
c^T (D + \Psi) c \leq P_R. \tag{21}
\]

Note that since the users cannot cooperate with each other, the interference avoidance operation can only be conducted at the relay, with which the power allocation factors for each pair are entangled together in the noise part (i.e., the off-diagonal entries of \(\Psi\) are non-zero). Therefore, the corresponding power constraint is non-convex.

In summary, the power allocation problem considered in this letter can be formulated as
\[
\max \quad R \tag{22a}
\]
\[
s.t. \quad c^T (D + \Psi) c \leq P_R. \tag{22b}
\]

Unfortunately, the problem (22) is non-convex following the non-convexity of the power constraint (22b). To our knowledge, there is no theoretically polynomial-time algorithm for such a non-convex problem.

B. Upper Bound and Suboptimal Power Allocation

In this subsection, we propose an alternative approach to this problem. The methodology here is to first enlarge the feasible region determined by the power constraint at the relay (22b) to its convex hull, such that the original problem is relaxed to a convex one. This will lead to an upper bound of the achievable sum rate. A suboptimal power allocation for the original problem is then obtained by scaling the solution to the relaxed problem such that the power constraint at the relay is satisfied with equality. Specifically, since the left-hand side of (22b) is lower bounded by
\[
c^T (D + \Psi) c
\]
\[
\geq c^T D c \cdot \left( 1 + \frac{c^T \Psi c}{c^T D c} \right) \geq c^T D c \cdot \left( 1 + \lambda_{\text{min}} \right),
\]

we can relax the power constraint at the relay as
\[
\sum_{m=1}^{K} c_m^T (d_{m,1} + d_{m,2}) + \sum_{m=K+1}^{K+L} c_m^T d_{m,1} \leq \frac{P_R}{1 + \lambda_{\text{min}}}, \tag{23}
\]

where \(\lambda_{\text{min}}\) is the smallest eigenvalue of \(D^{-1} \Psi\). Replacing (22b) with (23), we arrive at the following relaxed problem.

\[
\max \quad R \tag{24a}
\]
\[
s.t. \quad (23). \tag{24b}
\]

This problem is convex and can be solved using standard convex optimization tools such as Newton’s method. The optimized sum rate of (24) then serves as an upper bound for the achievable sum rate of our proposed relaying scheme.

A suboptimal power allocation for our proposed relaying scheme can be attained as follows. Let \(\{c_m\}_{m=1}^{K} = [1, \ldots, K + L]\) be the solution to (24). Then a feasible power allocation for (22) can be represented as
\[
e^o = [e_1^o, \ldots, e_{K+L}^o]^T\]

and the scaling factor \(\rho\) is selected such that the power constraint (22b) holds with equality, i.e., \(\rho = \sqrt{\frac{P_R}{(e_i^o)^T (D + \Psi) e_i^o}}\).

V. NUMERICAL RESULTS

In this section, we provide some numerical results based on the following system setting. The noise levels at the relay and all users are assumed the same, i.e., \(\sigma_{\text{NR}} = \sigma_{\text{NR}}\). Both the large scale path loss gain and the small scale Rayleigh fading are considered when generating the channel vector of each link. The distances between the users and the relay are independently and uniformly distributed in the interval \([0.1, 1]\). The path loss exponent is set at \(4\).

We first examine the performance of the proposed scheme in hybrid one-way and two-way relay networks. Consider a relay network with \(K = 2, L = 2\) and \(N = 5\). Fig. 1 plots the achievable sum rates of our proposed scheme with and without power allocation and the corresponding upper bound in such hybrid networks. For comparison, we also include the sum rate of a zero-forcing based scheme, in which the relay receives and re-transmits each signal stream in the nulling space of other users’ channel vectors. The following observations can be made from this figure.

- The proposed scheme outperforms zero-forcing relaying. This is because our scheme allows self-interference at the relay, which is later canceled at the destination, and thus suffers less projection loss than the zero-forcing one;
- A considerable sum rate increase is achieved after power allocation; and
- The proposed power allocation method performs very close to the upper bound in all SNR regions.

In Fig. 2, we compare the performance of multi-user relay networks with \(N = 5\) and different \(\{K, L\}\). We can see from the figure that the hybrid system with \(K = 2, L = 1\) performs the best in the low-to-medium SNR region, which confirms the necessity of analyzing the hybrid relay network. However, as \(P_R / \gamma > 16\,\text{dB}\), the pure two-way relay system outperforms the hybrid system. This is because at high SNRs the system throughput is mainly determined by the achievable degree of freedom. The pure two-way relay system supports 6 data streams in total. Comparatively, the hybrid one supports 5 data streams, which implies a lower achievable degree of freedom than that in the pure two-way
relay system. In general, two-way relaying has a higher spectrum/power efficiency than one-way relaying. However, a pure two-way relaying scheme may not always achieve the optimal performance, especially in the low-to-medium SNR range.

Next, we use an example to further demonstrate the necessity and potential benefit of designing hybrid relaying schemes. Consider a multi-pair two-way relay network with $K = 4$ and $N = 7$. Since such a pure two-way relay network is a special case of the hybrid networks discussed in this letter, we can conclude from (13) that all the 4 user pairs can transmit simultaneously using our proposed relay scheme. However, for the aim of system sum rate maximization, sometimes it is necessary to allow only a part of users to transmit such that they suffer less projection loss from the inter-pair interference avoidance operations. To this end, the active users can either be selected pair by pair, where a pair of users $\{U_{m,1}, U_{m,2}\}$ are either both selected for the information exchange or both idle, or be selected one by one where each user is selected individually, potentially leading to a hybrid network involving both one-way and two-way information transmissions. In Fig. 3, we plot the achievable sum rates of the above considered network based on our proposed relaying scheme and various user selection criteria. For each user selection criterion, the active user set is determined via exhaustive search aiming at maximizing the system sum rate. The design of more efficient user selection methods is beyond the scope of this letter. It is observed that the maximum sum rate can not be achieved by allowing as many user pairs as possible to transmit simultaneously. This is because that the projection loss induced by eliminating inter-pair interference may outweigh the multiplexing gain brought by transmitting more signal streams, especially when SNR is low. Compared with selecting the users pair by pair, the sum rate is improved significantly by selecting the users one by one, as the latter provides more flexibility in terms of the number of activated users as well the specific users that are activated, i.e., the partner of an activated user may stay idle.

VI. CONCLUSION

In this letter, we designed a relaying scheme for hybrid one-way and two-way relay networks and proposed a power allocation method at the relay to maximize the sum rate. Numerical results showed that our proposed hybrid scheme significantly outperforms the conventional zero-forcing relaying scheme and achieves notable throughput gain in pure two-way relay networks when combined with individual user selection.

REFERENCES