

Research Article

Distributed Beamforming Design for Nonregenerative Two-Way Relay Networks with Simultaneous Wireless Information and Power Transfer

Keyun Liao, Sai Zhao , Yusi Long, Gaofer Huang, and Dong Tang

School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou, Guangdong Province, China

Correspondence should be addressed to Sai Zhao; zhaosai@gzhu.edu.cn

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This paper considers the distributed beamforming design for a simultaneous wireless information and power transfer (SWIPT) in two-way relay network, which consists of two sources, K relay nodes and one energy harvesting (EH) node. For such a network, assuming perfect channel state information (CSI) is available, and we study two different beamforming design schemes. As the first scheme, we design the beamformer through minimization of the average mean squared error (MSE) subject to the total transmit power constraint at the relays and the energy harvesting constraint at the EH receiver. Due to the intractable expression of the objective function, an upper bound of MSE is derived via the approximation of the signal-to-noise ratio (SNR). Based on the minimization of this upper bound, this problem can be turned into a convex feasibility semidefinite programming (SDP) and, therefore, can be efficiently solved using interior point method. To reduce the computational complexity, a suboptimal beamforming scheme is proposed in the second scheme, for which the optimization problem could be recast to the form of the Rayleigh–Ritz ratio and a closed-form solution is obtained. Numerical results are provided and analyzed to demonstrate the efficiency of our proposed beamforming schemes.

1. Introduction

Harvesting energy from environment has become a preferred strategy to overcome the key challenge of limited lifetime of devices equipped with battery in wireless networks, e.g., wireless sensor network (WSN) or Bluetooth low-energy mesh (BLE Mesh) network. As an efficient energy harvesting technique, simultaneous wireless information and power transfer (SWIPT) has gained considerable research attention in the academic field [1–6]. The concept of SWIPT was first introduced and a capacity-energy function was first proposed to characterize the fundamental tradeoff between simultaneous energy and information transfer in [1]. Considering SWIPT in multiple-input single-output (MISO) multicasting systems [2], the authors minimize the base station (BS) transmit power by jointly optimizing the beamforming vector at BS and the power splitting parameters of mobile station. In [3], considering a multiple-input multiple-output (MIMO) wireless

broadcast scenario, where one receiver harvested energy and another receiver decoded information from the signals sent by a transmitter, two practical schemes, namely, time switching (TS) and power splitting (PS), were proposed. Motivated by the requirement of fifth generation, Xu et al. [4] investigated the cooperative SWIPT NOMA protocol design in single-input single-output (SISO) and multiple-input single-output (MISO). Meanwhile, the security of information transmission also became more and more important. Zhao et al. [5] considered the security of wireless network for SWIPT, which maximize the achievable secrecy rate subject to sum transmit power constraint at relays and energy harvesting (EH) constraint at the EH receiver. Aforementioned papers were investigated under perfect channel state information (CSI). In [6], the MIMO SWIPT system under the condition of imperfect CSI was studied.

Considering its advantage in enhancing spectral efficiency, two-way relay (TWR) network is extensively studied [7–10]. In the TWR network, two source nodes exchanged

information through a relay node, and the number of required time slots is reduced from four to two with the aid of analog network coding [7]. In [8], a cooperative relay scheme for distributed amplify-and-forward (AF) relays working under the TWR protocol was considered, and a closed-form solution was obtained. Considering the user fairness, a linear precoding design for relay in multiple-pair two-way MIMO relay systems was investigated [9]. Considering security, cooperative beamforming in cognitive two-way relay networks was studied in [10]. For SWIPT two-way relay channels, the authors of [11–15] considered the relay beamforming design for SWIPT in a nonregenerative TWR network with the objective to maximize the sum rate of TWR. Wen et al. [12] studied the joint source and relay design for MIMO two-way relay networks with SWIPT, which minimized the total mean square error guaranteeing sufficient energy harvested at the sources. The authors of [14, 15] developed a novel distributed energy beamforming scheme for realizing SWIPT in the TWR network, where the former considered two source node exchanged information via an EH relay node and the latter considered multiple-user exchanged messages with the help of an energy-constrained relay node. Considering imperfect CSI and energy efficiency, the robust optimization schemes of MIMO two-way relay networks were considered under the constraint of energy harvesting [16]. In the IoT networks or sensor networks, most of the nodes may have limited volume and limited computation capacity with limited energy supply, some of the relay nodes are providing data communication service, while other idle node(s) could harvest energy to prolong its/their life cycle. That is why we consider multiple relays in two-way transmission, while at the same time, an EH is placed to harvest energy. And to our best knowledge, there is little work on this system model by now.

The main contributions of our paper are summarized as follows:

- (1) We study the distributed beamforming design in SWIPT-based two-way multiple-relay networks. Differing from [14, 15], we consider the two-way SWIPT system with multiple relays, while only single relay is considered in [14, 15]. Our goal is to minimize the upper bound of average MSE while satisfying the harvested energy requirements of the EH receiver and the total power budgets of the multiple relays.
- (2) For the case of SWIPT-based two-way multiple-relay networks, the initial problem is a nonconvex problem. Through appropriate mathematical transformation, we could recast the initial problem into the semidefinite programming (SDP) problem. Then, we can obtain a quasi-optimal solution by applying semidefinite relaxation (SDR).
- (3) To avoid the high computational complexity resulting from solving the SDP problem, we find the suboptimal solution by converting the initial problem into the form of the Rayleigh–Ritz quotient, which is of low complexity.

The rest of this paper is organized as follows: in Section 2, the system model and the problem formulation are illustrated.

Section 3 presents our proposed methods to obtain the solutions to the problem of beamforming design. Section 4 constructs complexity analysis of two schemes and provides simulation results. Finally, Section 5 has a conclusion about the paper.

Notations: boldface lowercase and uppercase letters denote vectors and matrices, respectively. The transpose, conjugate, conjugate transpose, Frobenius norm, and trace of matrix \mathbf{A} are denoted as \mathbf{A}^T , \mathbf{A}^* , \mathbf{A}^H , $\|\mathbf{A}\|$, and $\text{tr}(\mathbf{A})$, respectively. $\text{vec}(\mathbf{A})$ denotes to stack the columns of a matrix \mathbf{A} into a single vector \mathbf{a} . \otimes denotes the Kronecker product. $\lambda_{\max}(\mathbf{A})$ and $\lambda_{\min}(\mathbf{A})$ denote the maximum and minimum eigenvalues of \mathbf{A} , respectively. $\mathbf{v}\{\mathbf{A}\}$ denotes the eigenvector of \mathbf{A} associating with the maximum eigenvalue. By $\mathbf{A} \succeq 0$, we mean that \mathbf{A} is positive semidefinite. \mathbf{I} is the identity matrix. $\mathcal{CN}(0, 1)$ denotes the distribution of a circularly symmetric complex Gaussian vector with mean vector 0 and variance 1.

2. System Model

We consider a collaborative network consisting of two source nodes, K AF relays using the two-way protocol, and one EH receiver as shown in Figure 1.

Each node in the whole network is equipped with a single antenna. All nodes are subject to the half-duplex mode. The two source nodes complete the information exchange with the help of K distributed relay nodes within two time slots. In the first time slot, both S_1 and S_2 transmit symbols to all relays in the same frequency band simultaneously. The symbol received by the k th relay can be describe as

$$r_k = \sqrt{P_1} h_{1k,f} s_1 + \sqrt{P_2} h_{2k,f} s_2 + z_k, \quad (1)$$

where P_i , $i \in \{1, 2\}$, are the transmit power at S_1 and S_2 , respectively; $h_{ik,f}$ are the channel fading coefficient from S_i to the k th relay, where $k \in \mathcal{K} = \{1, 2, 3, \dots, K\}$; s_i are the transmitted symbols from S_i , and $\mathbb{E}[|s_i|^2] = 1$; and $z_k \sim \mathcal{CN}(0, \sigma_k^2)$ is the additive white Gaussian noise (AWGN) at the k th relay in the first time slot. We assume perfect channel state information (CSI) of all channels is known to both source nodes. The relay will perform the channel estimation from both sources to multiple relays and feedback the CSI to both source nodes. The EH nodes perform channel estimation from sources to the EH node in the first slot and perform channel estimation from relay to EH nodes in the second slot, then feedback to the sources. The synchronisation is performed by synchronisation signals sent from sources to relays and EH nodes so that all relays and EH can be perfectly synchronized.

The symbol to be retransmitted by the k th relay is given by

$$t_k = w_k (\sqrt{P_1} h_{1k,f} s_1 + \sqrt{P_2} h_{2k,f} s_2 + z_k), \quad (2)$$

where w_k is the complex beamforming weight at the k th relay.

In the second time slot, the processed symbol t_k is transmitted from the k th relay to both S_1 and S_2 simultaneously, and the symbol received by S_1 and S_2 can be, respectively, written as

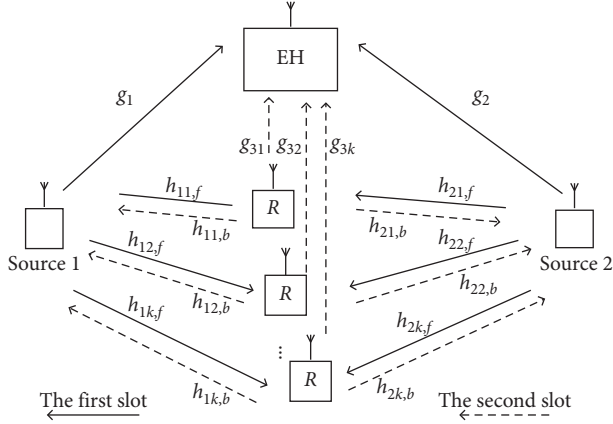


FIGURE 1: Illustration of the two-way relay network with SWIPT.

$$y_1 = \sum_{k=1}^K h_{1k,b} t_k + n_{21}, \quad (3)$$

$$y_2 = \sum_{k=1}^K h_{2k,b} t_k + n_{22}, \quad (4)$$

where $n_{2i} \in \mathcal{CN}(0, \sigma_i^2)$ is AWGN at S_i , respectively, in the second time slot and $h_{ik,b}$ are the channel fading coefficient from the k th relay to S_i , $k \in \mathcal{K} = \{1, 2, 3, \dots, K\}$.

Assume the channels are reciprocal during two time slots (e.g., under TDD mode), i.e., $h_{ik,f} = h_{ik,b} = h_{ik}$ for $i \in \{1, 2\}$. Since each source node knows both the channels associated itself with the relay nodes and the weighted coefficients w_k , it can subtract the self-interference from itself which is similar to [11]. After this operation, (3) and (4) become

$$\tilde{y}_1 = \sqrt{P_2} \sum_{k=1}^K h_{1k} w_k h_{2k} s_2 + \sum_{k=1}^K h_{1k} w_k z_k + n_{21}, \quad (5)$$

$$\tilde{y}_2 = \sqrt{P_1} \sum_{k=1}^K h_{2k} w_k h_{1k} s_1 + \sum_{k=1}^K h_{2k} w_k z_k + n_{22}. \quad (6)$$

The signal received by the EH receiver within two time slots can be, respectively, written as

$$\begin{aligned} e_1 &= \sqrt{P_1} g_1 s_1 + \sqrt{P_2} g_2 s_2 + n_{EH}, \\ e_2 &= \sqrt{P_1} \sum_{k=1}^K g_{3k} w_k h_{1k} s_1 + \sqrt{P_2} \sum_{k=1}^K g_{3k} w_k h_{2k} s_2 \\ &\quad + \sum_{k=1}^K g_{3k} w_k z_k + n_{EH}, \end{aligned} \quad (7)$$

where g_i denotes the channel fading coefficient from source node S_1 to the EH receiver, and g_{3k} , $k \in \mathcal{K}$, denotes the channel fading coefficient from the k th relay to the EH receiver, and $n_{EH} \sim \mathcal{CN}(0, \sigma_{EH}^2)$ denotes AWGN at EH receiver. For simplicity, the noise powers at two sources, K relays, and EH receiver, if not specified, are $\sigma_1^2 = \sigma_2^2 = \sigma_k^2 = \sigma_{EH}^2 = \sigma^2$.

The harvested energy at the EH receiver during two time slots is given, respectively:

$$\begin{aligned} E_1 &= P_1 |g_1|^2 + P_2 |g_2|^2, \\ E_2 &= P_1 \left| \sum_{k=1}^K g_{3k} w_k h_{1k} \right|^2 + P_2 \left| \sum_{k=1}^K g_{3k} w_k h_{2k} \right|^2 + \sigma^2 \sum_{k=1}^K |g_{3k} w_k|^2. \end{aligned} \quad (8)$$

In this paper, we will design a distributed relay beamforming to minimize the average MSE of bidirectional transmissions of two source nodes subject to the EH constraint and the total relay power constraint.

The MSE of each received symbol in traditional multiple-input multiple-output (MIMO) systems can be expressed by its signal-to-noise ratio (SNR) as $\text{MSE} = 1/(\text{SNR} + 1)$ if the Wiener filter is used at the receiver [17]. In two-way relay networks, the average MSE of the received symbols for bidirectional transmissions of two source nodes in (5) and (6) can be described as

$$\text{MSE} = 0.5(1 + \text{SNR}_1)^{-1} + 0.5(1 + \text{SNR}_2)^{-1}, \quad (9)$$

where SNR_i are the SNR for the received symbols for S_1 and S_2 , respectively.

To simplify equation (9), the average MSE can be tightly approximated in the high SNR regime as

$$\widetilde{\text{MSE}} = 0.5(\text{SNR}_1)^{-1} + 0.5(\text{SNR}_2)^{-1} \geq \text{MSE}, \quad (10)$$

where

$$\begin{aligned} \text{SNR}_1 &= \frac{P_2 \left| \sum_{k=1}^K h_{1k} w_k h_{2k} \right|^2}{\sigma^2 \left(1 + \sum_{k=1}^K |h_{1k}|^2 |w_k|^2 \right)}, \\ \text{SNR}_2 &= \frac{P_1 \left| \sum_{k=1}^K h_{2k} w_k h_{1k} \right|^2}{\sigma^2 \left(1 + \sum_{k=1}^K |h_{2k}|^2 |w_k|^2 \right)}. \end{aligned} \quad (11)$$

It is noted that $\widetilde{\text{MSE}}$ is the upper bound of MSE. Based on $\widetilde{\text{MSE}}$, the upper bound of MSE minimization problem can be formulated as

$$\min_{w_k} \widetilde{\text{MSE}}, \quad (12a)$$

$$\text{s.t.} \quad \sum_{k=1}^K |w_k|^2 (P_1 |h_{1k}|^2 + P_2 |h_{2k}|^2 + \sigma^2) \leq P_3, \quad (12b)$$

$$E_1 + E_2 \geq Q. \quad (12c)$$

It is noted that the optimization problem of the upper bound of MSE is a nonconvex problem due to the nonconvex of objective function and EH constraint. In the following section, we propose schemes to solve problem (12a)–(12c).

3. Beamforming Design for Multiple Relays

Firstly, the objective function in problem (12a)–(12c) can be rewritten as

$$\widetilde{\text{MSE}} = \frac{0.5(\sigma^2 + \sigma^2 \mathbf{w}^H \mathbf{B}_1^H \mathbf{B}_1 \mathbf{w})}{P_1 \mathbf{w}^H \mathbf{g}_e^* \mathbf{g}_e^T \mathbf{w}} + \frac{0.5(\sigma^2 + \sigma^2 \mathbf{w}^H \mathbf{B}_2^H \mathbf{B}_2 \mathbf{w})}{P_2 \mathbf{w}^H (\mathbf{g}_e^* \mathbf{g}_e^T) \mathbf{w}}, \quad (13)$$

where

$$\begin{aligned}\mathbf{w} &\triangleq (w_1, \dots, w_k, \dots, w_K)^T, \\ \mathbf{B}_1 &\triangleq \text{diag}\{(h_{21}, \dots, h_{2k}, \dots, h_{2K})^T\}, \\ \mathbf{B}_2 &\triangleq \text{diag}\{(h_{11}, \dots, h_{1k}, \dots, h_{1K})^T\}, \\ \mathbf{g}_e &\triangleq (h_{11}h_{21}, \dots, h_{1k}h_{2k}, \dots, h_{1K}h_{2K})^T.\end{aligned}\quad (14)$$

Secondly, it is noted that the optimal beamforming vector \mathbf{w} for problem (12a)–(12c) should guarantee that the total transmit power constraint (12b) at relays is active, i.e., (12b) can be written equivalently as

$$\mathbf{w}^H \frac{\mathbf{B}_3}{P_3} \mathbf{w} = 1, \quad (15)$$

where $\mathbf{B}_3 \triangleq \text{diag}\{(P_1|h_{11}|^2 + P_2|h_{21}|^2 + \sigma^2, \dots, P_1|h_{1k}|^2 + P_2|h_{2k}|^2 + \sigma^2, \dots, P_1|h_{1K}|^2 + P_2|h_{2K}|^2 + \sigma^2)^T\}$.

Thirdly, substituting (15) into (12c), the constraint in (12c) can be recast as

$$\mathbf{w}^H \left(P_1 \mathbf{g}_{h1}^* \mathbf{g}_{h1}^T + P_2 \mathbf{g}_{h2}^* \mathbf{g}_{h2}^T + \sigma^2 \mathbf{g}_3 \mathbf{g}_3^H - \frac{\tilde{Q}}{P_3} \mathbf{B}_3 \right) \mathbf{w} \geq 0, \quad (16)$$

where

$$\begin{aligned}\mathbf{g}_{h1} &\triangleq (g_{31}h_{11}, \dots, g_{3K}h_{1K})^T, \\ \mathbf{g}_{h2} &\triangleq (g_{31}h_{21}, \dots, g_{3K}h_{2K})^T, \\ \tilde{Q} &\triangleq Q - E_1, \\ \mathbf{g}_3 &\triangleq \text{diag}\{(g_{31}, \dots, g_{3k}, \dots, g_{3K})^T\},\end{aligned}\quad (17)$$

and Q denotes the threshold of the harvested energy at the EH receiver.

We choose $0 \leq Q \leq Q_{\max}$, where

$$Q_{\max} = E_1 + \lambda_{\max}(\mathbf{B}_3^{-1} \mathbf{B}_4) P_3, \quad (18)$$

where $\mathbf{B}_4 = P_1 \mathbf{g}_{h1}^* \mathbf{g}_{h1}^T + P_2 \mathbf{g}_{h2}^* \mathbf{g}_{h2}^T + \sigma^2 \mathbf{g}_3 \mathbf{g}_3^H$. And $\lambda_{\max}(\cdot)$ indicates the maximum eigenvalue of a matrix. Substituting (15) into (13), ignoring the coefficient 0.5, problem (12a)–(12c) can be reformulated as

$$\min_{\mathbf{w}} \quad \frac{\mathbf{w}^H ((\sigma^2 \mathbf{B}_3 / P_1 P_3) + (\sigma^2 \mathbf{B}_1^H \mathbf{B}_1 / P_1) + (\sigma^2 \mathbf{B}_3 / P_2 P_3) + (\sigma^2 \mathbf{B}_2^H \mathbf{B}_2 / P_2)) \mathbf{w}}{\mathbf{w}^H (\mathbf{g}_e^* \mathbf{g}_e^T) \mathbf{w}}, \quad (19a)$$

$$\text{s.t.} \quad \mathbf{w}^H \left(\frac{\mathbf{B}_3}{P_3} \right) \mathbf{w} = 1, \quad (19b)$$

$$\mathbf{w}^H \left(\mathbf{B}_4 - \frac{\tilde{Q}}{P_3} \mathbf{B}_3 \right) \mathbf{w} \geq 0. \quad (19c)$$

In optimization problem (19a)–(19c), we have transformed the inequality constraint of total relay transmit power into an equality constraint. This is because the objective function and the constraint in (15) is homogeneous in \mathbf{w} . An arbitrary positive scaling of \mathbf{w} has no effect on the value of the objective function. Furthermore, if \mathbf{w} satisfies the constraint, an arbitrary positive scaling of \mathbf{w} also satisfies the constraint.

3.1. The Local Optimal Beamforming Scheme. The optimization problem (19a)–(19c) is a fractional quadratically constrained quadratic problem (QCQP) which is intractable. We transform the problem (19a)–(19c) into the following fractional semidefinite programming (SDP) problem [18]:

$$\min_{\mathbf{W}} \quad \frac{\text{Tr}(\mathbf{C}_1 \mathbf{W})}{\text{Tr}(\mathbf{C}_2 \mathbf{W})}, \quad (20a)$$

$$\text{s.t.} \quad \text{Tr}(\mathbf{C}_3 \mathbf{W}) = 1, \quad (20b)$$

$$\text{Tr}(\mathbf{C}_4 \mathbf{W}) \geq 0, \quad (20c)$$

where

$$\begin{aligned}\mathbf{C}_1 &= \sigma^2 \left(\frac{\mathbf{B}_3}{P_1 P_3} + \frac{\mathbf{B}_1^H \mathbf{B}_1}{P_1} + \frac{\mathbf{B}_3}{P_2 P_3} + \frac{\mathbf{B}_2^H \mathbf{B}_2}{P_2} \right), \\ \mathbf{C}_2 &= \mathbf{g}_e^* \mathbf{g}_e^T, \\ \mathbf{C}_3 &= \frac{\mathbf{B}_3}{P_3},\end{aligned}\quad (21)$$

$$\mathbf{C}_4 = \mathbf{B}_4 - \frac{\tilde{Q}}{P_3} \mathbf{B}_3,$$

$$\mathbf{W} = \mathbf{w} \mathbf{w}^H.$$

It is noted that the rank one constraint $\text{Rank}(\mathbf{W}) = 1$ has been removed within the problem (20a)–(20c), and the problem (20a)–(20c) is a quasi-convex optimization problem.

We have the following proposition.

Proposition 1. *The fractional SDP problem (20a)–(20c) can be written equivalent as*

$$\min_{\mathbf{W}} \text{Tr}(\mathbf{C}_1 \mathbf{W}), \quad (22a)$$

$$\text{s.t.} \quad \text{Tr}(\mathbf{C}_2 \mathbf{W}) = 1, \quad (22b)$$

$$\text{Tr}(\mathbf{C}_3 \mathbf{W}) = 1, \quad (22c)$$

$$\text{Tr}(\mathbf{C}_4 \mathbf{W}) \geq 0. \quad (22d)$$

Proof of Proposition 1. Suppose that (t_1, \mathbf{W}_1^o) and (t_2, \mathbf{W}_2^o) are the optimal value and optimal solution to the problems (20a)–(20c) and (22a)–(22d), respectively. It is obvious that \mathbf{W}_2^o is feasible to problem (20a)–(20c). When $\mathbf{W} = \mathbf{W}_2^o$, the objective value of (20a)–(20c) is t_2 . Therefore, $t_2 \geq t_1$.

On the contrary, it is easy to prove that $\mathbf{W}_1^o / \text{Tr}(\mathbf{C}_2 \mathbf{W}_1^o)$ is the feasible to problem (22a)–(22d). When $\mathbf{W} = \mathbf{W}_1^o / \text{Tr}(\mathbf{C}_2 \mathbf{W}_1^o)$, the objective value of (22a)–(22d) is t_1 . Therefore, $t_1 \geq t_2$. That means, problems (20a)–(20c) and (22a)–(22d) have the same optimal values, e.g., $t_1 = t_2$. Therefore, problem (20a)–(20c) is equivalent to (22a)–(22d).

Suppose that \mathbf{W}^o is the optimal solution to the problem (22a)–(22d). If $\text{Rank}(\mathbf{W}^o) = 1$, the optimal solution to problem (20a)–(20c) is \mathbf{W}_1^o which can be obtained by the eigenvalue decomposition technique, i.e., $\mathbf{W}_1^o = \sqrt{c} \mathbf{u}$, where c and \mathbf{u} denote the eigenvalue and eigenvector of \mathbf{W}^o , respectively. In the case of $\text{Rank}(\mathbf{W}^o) \geq 2$, we apply the Gaussian randomization technique [9] to obtain the final solution \mathbf{W}_1^o of problem (19a)–(19c) from the solution of problem (20a)–(20c). To obtain the final solution of initial problem (12a)–(12c), we also need to scale \mathbf{W}_1^o to satisfy the relay power constraint.

3.2. The Closed-Form Beamforming Scheme. To reduce the computational complexity, we propose a suboptimal closed-form solution to the problem (19a)–(19c). Define \mathbf{U} as a matrix which consists of the a ($1 \leq a \leq K$) eigenvectors of matrix \mathbf{C}_4 which are associated with the eigenvalues being greater than zero. We have

$$\mathbf{w} = \mathbf{U} \mathbf{x}, \quad (23)$$

where \mathbf{x} is an arbitrary vector such that

$$\mathbf{w}^H \mathbf{C}_4 \mathbf{w} \geq 0. \quad (24)$$

Substituting (24) into problem (19a)–(19c), we have the equivalent maximization problem:

$$\max_{\mathbf{x}} \frac{\mathbf{x}^H \mathbf{D}_2 \mathbf{x}}{\mathbf{x}^H \mathbf{D}_1 \mathbf{x}} \quad (25)$$

$$\text{s.t.} \quad \mathbf{x}^H \mathbf{D}_3 \mathbf{x} = 1,$$

where

$$\begin{aligned} \mathbf{D}_1 &= \mathbf{U}^H \mathbf{C}_1 \mathbf{U}, \\ \mathbf{D}_2 &= \mathbf{U}^H \mathbf{C}_2 \mathbf{U}, \\ \mathbf{D}_3 &= \mathbf{U}^H \mathbf{C}_3 \mathbf{U}. \end{aligned} \quad (26)$$

Introduce $\tilde{\mathbf{x}} = \mathbf{D}_3^{1/2} \mathbf{x}$ so that $\mathbf{x} = \mathbf{D}_3^{-(1/2)} \tilde{\mathbf{x}}$. Substituting \mathbf{x} into (25), we are able to transform problem (25) into the following form:

$$\max_{\tilde{\mathbf{x}}} \frac{\tilde{\mathbf{x}}^H \mathbf{G}_2 \tilde{\mathbf{x}}}{\tilde{\mathbf{x}}^H \mathbf{G}_1 \tilde{\mathbf{x}}}, \quad (27a)$$

$$\text{s.t.} \quad \tilde{\mathbf{x}}^H \tilde{\mathbf{x}} = 1, \quad (27b)$$

where

$$\begin{aligned} \mathbf{G}_1 &= (\mathbf{D}_3^{-(1/2)})^H \mathbf{D}_1 \mathbf{D}_3^{-(1/2)}, \\ \mathbf{G}_2 &= (\mathbf{D}_3^{-(1/2)})^H \mathbf{D}_2 \mathbf{D}_3^{-(1/2)}. \end{aligned} \quad (28)$$

It is noted that the problem (27a) and (27b) is a generalized Rayleigh quotient problem [16]. Defining $\mathbf{q} = \mathbf{G}_1^{1/2} \tilde{\mathbf{x}}$, we can rewrite (27a) and (27b) as

$$\max_{\mathbf{q}} \frac{\mathbf{q}^H (\mathbf{G}_1^H)^{1/2} \mathbf{G}_2 \mathbf{G}_1^{1/2} \mathbf{q}}{\mathbf{q}^H \mathbf{q}}. \quad (29)$$

Thus, the optimal solution to (29) can be obtained as

$$\begin{aligned} \mathbf{q} &= v_{\max} \left\{ (\mathbf{G}_1^H)^{1/2} \mathbf{G}_2 \mathbf{G}_1^{1/2} \right\} \\ &= (\mathbf{G}_1^H)^{1/2} (\mathbf{D}_3^H)^{-(1/2)} \mathbf{U}^H \mathbf{g}_e^*, \end{aligned} \quad (30)$$

where $v_{\max}\{\mathbf{A}\}$ denotes the eigenvector corresponding to the largest eigenvalue of matrix \mathbf{A} . Using (30), we have

$$\begin{aligned} \tilde{\mathbf{x}} &= \mathbf{G}_1^{1/2} \mathbf{q} \\ &= \kappa \mathbf{G}_1^{1/2} (\mathbf{G}_1^H)^{1/2} (\mathbf{D}_3^H)^{-(1/2)} \mathbf{U}^H \mathbf{g}_e^*, \end{aligned} \quad (31)$$

where $\kappa = 1 / \|\mathbf{G}_1^{1/2} (\mathbf{G}_1^H)^{1/2} (\mathbf{D}_3^H)^{-(1/2)} \mathbf{U}^H \mathbf{g}_e^*\|$ is used to normalize $\tilde{\mathbf{x}}$ that satisfies the constraint (27b). Substituting (31) into $\mathbf{x} = \mathbf{D}_3^{-(1/2)} \tilde{\mathbf{x}}$ and combining (23), we have

$$\begin{aligned} \mathbf{w} &= \kappa \mathbf{U} \mathbf{D}_3^{-(1/2)} \mathbf{G}_1^{1/2} (\mathbf{G}_1^H)^{1/2} (\mathbf{D}_3^H)^{-(1/2)} \mathbf{U}^H \mathbf{g}_e^* \\ &= \kappa (\mathbf{U} \mathbf{D}_3^{-(1/2)} \mathbf{G}_1^{1/2}) (\mathbf{U} \mathbf{D}_3^{-(1/2)} \mathbf{G}_1^{1/2})^H \mathbf{g}_e^*. \end{aligned} \quad (32)$$

4. Simulation Results

In the section, we present the simulation results of our proposed beamforming schemes. We assume that the channel from the source node S_i to the k th relay is modeled as $h_{ik} = d_{i,k}^{-(\chi/2)} \tilde{h}_{ik}$ and the channel from the source node S_i to the EH receiver is modeled as $g_i = d_{i,EH}^{-(\chi/2)} \tilde{g}_i$. The channel from the k th relay to the EH receiver is modeled as $g_{3k} = d_{k,EH}^{-(\chi/2)} \tilde{g}_{3k}$, where $d_{i,k}$ is the distance between S_i and the k th relay; $d_{i,EH}$ is the distance between S_i and the EH receiver; $d_{k,EH}$ is the distance between the k th relay and the EH receiver; $\chi = 3$ is the path loss exponent; and \tilde{h}_{ik} , \tilde{g}_i , and \tilde{g}_{3k} are the independent identically distributed (i.i.d.) Rayleigh fading channels, where $i \in \{1, 2\}$, $k \in \mathcal{K}$. We consider a symmetric network with $d_{1,EH} = d_{2,EH} = 8$ m, and K relays are symmetrically placed at the two sides of the EH receiver with $d_{2j+1,EH} = d_{2j,EH} = j * 6$ m, where $j \in \{1, \dots, K/2\}$. Through all the simulations, the transmit power of two

sources, if not specified, are $P_1 = P_2 = 10$ dB, and the noise variance is set to be $\sigma^2 = -25$ dB. The number of Monte Carlo simulations is set to 1000.

In the simulation, different beamforming schemes are considered including the proposed two schemes, i.e., local optimal scheme (denoted as “Local-optimal”), closed-form scheme (denoted as “Closed-form”), and the global optimal scheme (denoted as “Global-optimal”) in [11]. The “Global-optimal” scheme obtains the global optimal solution based on the two-dimensional search and semidefinite programming.

Figure 2 shows the average sum rate of both S_1 -to- S_2 - and S_2 -to- S_1 -directional transmissions versus P_3 in the underlying networks, comparing the “Global-optimal” scheme, “Local-optimal” scheme, and “Closed-form” scheme. Here, we consider the threshold of the EH constraint is $Q = 0.5Q_{\max}$ and the number of relay is $K = 4$. We observe that the “Global-optimal” scheme outperforms the proposed schemes “Local-optimal” scheme and “Closed-form” scheme. Meanwhile, the “Local-optimal” scheme has better performance than the “Closed-form” scheme. It is also noted that as P_3 increases, the average sum rates increase for three schemes.

In Figure 3, we compare three schemes in terms of average sum rate versus various EH thresholds, where $Q = \tau Q_{\max}$, $K = 4$, and $P_3 = 25$ dB. It is noted that, for different EH thresholds, the “Global-optimal” scheme has the best performance, and the “Local-optimal” scheme outperforms the “Closed-form” scheme. It is also noted that as τ increases, the average sum rates decrease for all three schemes.

In Figure 4, we present the average sum rate comparison of three schemes for different number of relays when the transmit power of relay $P_3 = 40$ dB and the threshold of EH constraint $Q = 0.1Q_{\max}$. It is found that the “Global-optimal” scheme has the best performance and the “Closed-form” scheme has the worst performance. With the increase of the number of relays, the average sum rate of the three schemes increases.

Here, we provide the complexity analysis of the “Global-optimal” scheme, “Local-optimal” scheme, and “Closed-form” scheme. According to [20], the complexity of obtaining an optimal solution for an SDP problem can be approximated as $\mathcal{O}(\max(m, n)^4 \sqrt{n} \log(1/\epsilon))$, where ϵ denotes the solution accuracy and m and n are the number of constraints and the dimension of the matrix, respectively.

- (i) For the “Global-optimal” scheme, $m = 4$ and $n = K$. Thus, the computational complexity of obtaining an global optimal solution is $\mathcal{O}((T \max(m, K)^4 \sqrt{n} \log(1/\epsilon)) + n_{rd})$ where T is the average iteration number of the two-dimensional search and n_{rd} is the complexity of the Gaussian randomization.
- (ii) For the “Local-optimal” scheme, the computational complexity is from the SDP problem (22a)–(22d), $m = 3$ and $n = K$. Therefore, the overall computational complexity of (22a)–(22d) is $\mathcal{O}(\max(m, K)^4 \sqrt{n} \log(1/\epsilon)) + n_{rd}$.

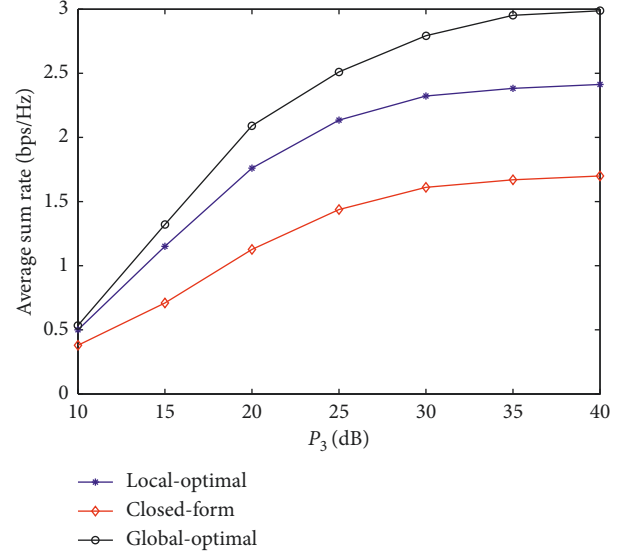


FIGURE 2: Average sum rate versus P_3 when the EH threshold $Q = 0.5Q_{\max}$ and $K = 4$.

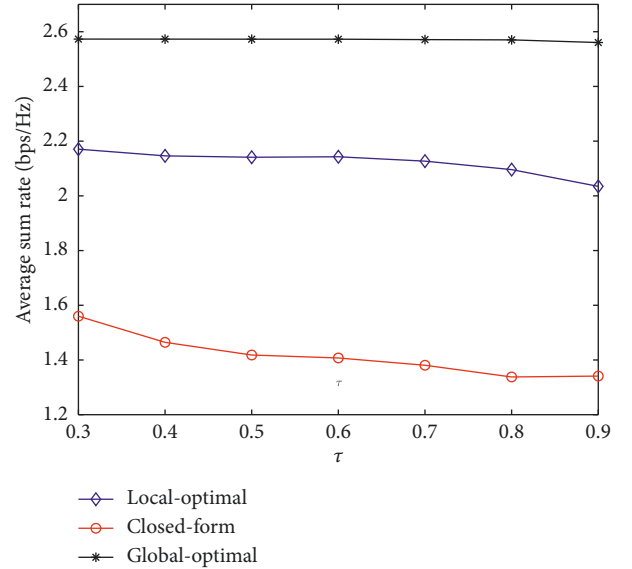


FIGURE 3: Average sum rate versus τ when the transmit power to noise power ratio of relay $P_3 = 25$ dB and $K = 4$.

- (iii) For the “Closed-form” scheme, the main computational complexity is to solve the function of the problem (27a) and (27b). The computation of the generalized eigenvector of matrix pair (G_2, G_1) requires $\mathcal{O}(a^3)$ arithmetic operations. Thus, the total computational complexity of the “Closed-form” scheme is $\mathcal{O}(a^3)$.

Obviously, the computational complexity of the “Global-optimal” scheme is very high due to the two-dimensional search. The “Local-optimal” scheme has comparatively much lower computational complexity than the “Global-optimal” scheme, and the “Closed-form” scheme has the lowest computational complexity.

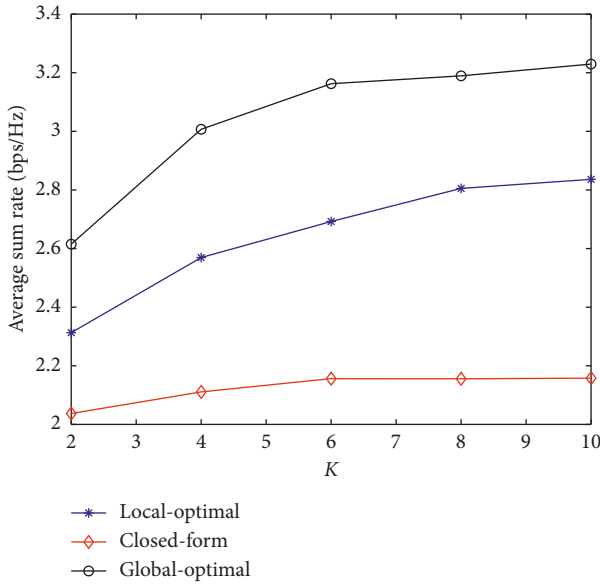


FIGURE 4: Average sum rate versus different number of relays when the EH threshold $Q = 0.1Q_{\max}$ and the transmit power at relays $P_3 = 40$ dB.

5. Conclusion

In this paper, we investigate the low complexity distributed beamforming scheme for the two-way multiple relays with SWIPT system. Though the “Global-optimal” scheme in [11] outperforms the proposed schemes, its computational complexity is very high compared to the two proposed schemes. The “Local-optimal” beamforming scheme has better performance than the “Closed-form” beamforming scheme; however, the computational complexity of the former is higher than that of the latter. Simulation results have shown the effectiveness of the proposed schemes. The multiple antennas equipped with each node in the system and more sophisticated EH model will be considered as an extension research of this paper.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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