Power Control and Beamforming Design for SWIPT in AF Two-Way Relay Networks

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***Abstract*—In this paper, we study the problem of joint power control and beamforming design for simultaneous wireless information and power transfer (SWIPT) in an amplify-and-forward (AF) based two-way relaying (TWR) network. The considered system model consists of two source nodes and a relay node. Two single-antenna source nodes receive information and energy simultaneously via power splitting (PS) from the signals sent by a multi-antenna relay node. Our objective is to maximize the weighted sum power at the two source nodes subject to quality of service (QoS) constraints and the transmit power constraints. However, the joint optimization of the relay beamforming matrix, the source transmit power and PS ratio is intractable. To find a closed-form solution of the formulated problem, we decouple the primal problem into two subproblems. In the first problem, we intend to optimize the beamforming vectors for given transmit powers and PS ratio. In the second subproblem, we optimize the remaining parameters with obtained beamformers. It is worth noting that although the corresponding subproblem are nonconvex, the optimal solution of each subproblem can be found by using certain techniques. The iterative optimization algorithm finally converges. Simulation results verify the effectiveness of the proposed joint design.**

I. Introduction

Simultaneous wireless information and power transfer (SWIPT) is a promising energy harvesting (EH) technique to prolong the operational time of energy-constrained nodes in wireless networks [1], [2]. Recently, SWIPT has been investigated for various wireless channels, e.g., the point-to-point additive white Gaussian noise (AWGN) channel [3], the frequency selective channels [4], the fading AWGN channel [5], the multiple-input-multiple-output (MIMO) channel [6], and the multiple-input-single-output (MISO) broadcast channel [7].

Besides the above studies related to one-hop transmission, the SWIPT technique has also been extended to wireless relay networks [8]–[14]. For the one-way single-antenna relay channel, two protocols, namely time switching (TS) and power splitting (PS), are proposed for amplify-and-forward (AF) relay networks in [8], [9]. Later on, SWIPT was extended to a full-duplex wireless-powered one-way relay channel in [10], [11], where the data and energy queues of the relay are updated simultaneously in every time slot. However, compared with the one-way relaying (OWR), two-way relaying (TWR) can further improve system spectral efficiency, the SWIPT protocols for TWR channel recently have attracted much attention. In [12], the authors provided a SWIPT protocol in two-way AF relaying channels, where two sources exchange information via an energy harvesting relay node. In [13], the authors investigated the sum-rate maximization problem in two-way AF relaying systems, where two source nodes harvest energy from multiple relay nodes. In [14], the authors studied the relay beamforming design problem for SWIPT in a non-regenerative two-way AF multi-antenna relay network. However, most studies on SWIPT in relay networks focused on energy-constrained relay nodes [8]–[12]. As a matter of fact, in some scenarios (such as cellular network), the terminals are often powered by the energy limited batteries. How to prolong the operational time of the terminals has become the issue with the growing of the power consumed caused by traffic increases. Therefore, EH in such kind of scenarios is also particularly important as it can provide a much more convenient solution for charging the batteries of the terminals or acting as a power source.

In this paper, similar to [13], [14], we consider a two-way AF SWIPT system with battery-limited source nodes and a relay node that acts also as a source of energy. However, the authors in [13] assumed that the source node is able to decode information and extract power simultaneously, which, as explained in [6], may not hold in practice. The authors in [14] assumed the case of separated EH and information decoding (ID) receivers, which leads to that the system has become more complicated. In this paper, thanks to the PS scheme [6], we study a TWR based PS-SWIPT system where the received signal at the source is split for ID and EH. In particular, different from [13], [14], our objective is to maximize the weighted sum power at two source nodes subject to a given minimum signal-to-interference-and-noise ratio (SINR) constraint at source nodes and a maximum transmit power constraint at each node. Since in the cellular networks, SINR is a important metric for maintaining a given throughput while maximizing energy transfer of the terminals by the relay. The latter maximizes the operational time of the terminals which can be another important metric in the scenarios. To the authors' best knowledge, the joint beamforming, power allocation and PS optimization for this new setup has not been studied in existing works.

Under the above setup, we first propose a two-phase relaying protocol based on PS with the splitting ratio ρ. Next, for the AF relaying strategy, we formulate the joint optimization as a nonconvex quadratically constrained problem. For the nonconvex optimization problem, we find a solution by decoupling the primal problem into two subproblems.

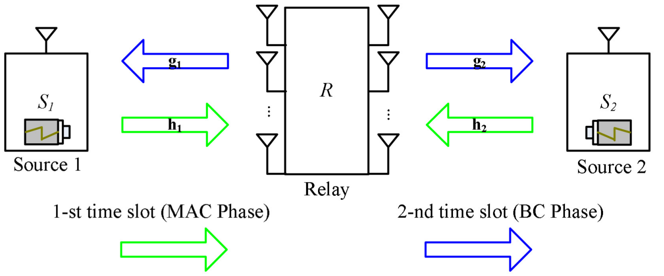

Fig. 1. A two-time slot TWR system. (a) 1-st time slot (MAC phase); (b) 2-nd time slot (BC phase).

Then, an iterative optimization algorithm is proposed for two subproblems to jointly optimize the relay beamforming matrix, the source transmit power and PS ratio. Finally, we provide numerical results to evaluate the performance of the proposed joint optimal design.

Notations: Boldface lowercase and uppercase letters denote vectors and matrices, respectively. For a square matrix $\mathbf{A}$, $\mathbf{A}^T$, $\mathbf{A}^*$, $\mathbf{A}^H$, $\mathrm{Tr}(\mathbf{A})$, $\mathrm{Rank}(\mathbf{A})$ and $||\mathbf{A}||$ denote its transpose, conjugate, conjugate transpose, trace, rank, and Frobenius norm, respectively. $\mathbf{A} \succeq 0$ indicates that $\mathbf{A}$ is a positive semidefinite matrix. $\mathrm{vec}(\mathbf{A})$ denotes the vectorization operation by stacking the columns of $\mathbf{A}$ into a single vector $\mathbf{a}$. $\mathbb{E}(\cdot)$ denotes the statistical expectation. $\otimes$ denotes the Kronecker product. $\mathbf{0}$ and $\mathbf{I}$ denote the zero and identity matrix, respectively. The distribution of a circular symmetric complex Gaussian vector with mean vector $\mathbf{x}$ and covariance matrix $\mathbf{\Sigma}$ is denoted by $\mathcal{CN}(\mathbf{x}, \mathbf{\Sigma})$. $\mathbb{C}^{x \times y}$ denotes the $x \times y$ domain of complex matrices.

II. System Model and Problem Formulation

Consider a half-duplex TWR system where two single-antenna source nodes S_1 and S_2 exchange information with each other through an N-antenna relay node, R. Specifically, the two source nodes are powered by the energy limited batteries, i.e., the sources themselves have initial powers to support their circuitry energy consumption and need to replenish their energy by wireless power transfer from the relay, as shown in Fig. 1. The channel vectors from S_1 and S_2 to the relay are denoted by $\mathbf{h}_1$ and $\mathbf{h}_2$, respectively, and the channel vectors from the relay to S_1 and S_2 are denoted by $\mathbf{g}_1$ and $\mathbf{g}_2$, respectively. To further improve the spectral efficiency, the two-phase PS-based protocol is used to realize bidirectional communication. Note that here, by assuming a PS ratio, ρ, the transmit signal from the relay is used to simultaneously achieve information and power transfer. For simplicity, we assume that two source nodes cannot communicate with each other directly due to large path loss or heavy shadowing. It is assumed that each node has perfect full CSIT. In addition, we also assume that all the channels are block-fading, i.e., the channels remain constant during each transmission slot, but change from one slot to another.

Based on the above system setup, the received signal at the relay after the first phase, i.e., *the multiple access (MAC) phase*, is given by

$$\mathbf{y}_R = \mathbf{h}_1 x_1 + \mathbf{h}_2 x_2 + \mathbf{n}_R, \tag{1}$$

where x_i, for $i \in \{1, 2\}$, represents the transmit signal from node S_i with $\mathbb{E}(|x_i|^2) = P_i$, respectively, and $\mathbf{n}_R$ denotes the additive complex Gaussian noise vector at the relay following $\mathcal{CN}(\mathbf{0}, \sigma_r^2 I_N)$.

Upon receiving $\mathbf{y}_R$, the relay node performs the amplified processing and then forwards its signal to the source nodes in the second phase, also referred as *broadcast (BC) phase*. Let the transmit signal from the relay be denoted by

$$\mathbf{x}_R = \mathbf{W}\mathbf{h}_1 x_1 + \mathbf{W}\mathbf{h}_2 x_2 + \mathbf{W}\mathbf{n}_R + \mathbf{x}, \tag{2}$$

where $\mathbf{W}$ represents the precoding matrix used at the relay. Note that, here, we include a new signal $\mathbf{x}$, which provides us with more degrees of freedom to optimize power transfer from relay to the source nodes [15]. In addition, we assume that the relay node has the maximum transmit power P_r, i.e., $\mathrm{Tr}\{\mathbb{E}(\mathbf{x}_R\mathbf{x}_R^H)\} \leq P_r$, which is equivalent to

$$P_1||\mathbf{W}\mathbf{h_1}||_2^2 + P_2||\mathbf{W}\mathbf{h_2}||_2^2 + \mathrm{Tr}(\mathbf{Q}_x) + \sigma_r^2||\mathbf{W}||_F^2 \leq P_r, \tag{3}$$

where $\mathbf{Q}_x = \mathbb{E}(\mathbf{x}\mathbf{x}^H)$ is the covariance matrix of $\mathbf{x}$. Then, the radio-frequency (RF) signals, $\tilde{y}_i$ received at the two nodes in the second $T/2$ time interval are given by

$$\tilde{y}_i = \mathbf{g}_i^T\mathbf{W}\mathbf{h}_{\bar{i}}\tilde{x}_{\bar{i}} + \mathbf{g}_i^T\mathbf{W}\mathbf{h}_i\tilde{x}_i + \mathbf{g}_i^T\tilde{\mathbf{x}} + \mathbf{g}_i^T\mathbf{W}\tilde{\mathbf{n}}_R + n_{i,d}, \tag{4}$$

where $\bar{i} = 2$ if $i = 1$ and $\bar{i} = 1$ if $i = 2$, and $n_{i,d} \sim \mathcal{CN}(0, \sigma_{i,d}^2)$ represents the additive Gaussian noise due to the receiving antenna [9]. The received signal $\tilde{y}_i$ at each end node is split into two portions for ID and EH. Let $\rho \in (0, 1)$ be the power splitting ratio, meaning that $\sqrt{1-\rho}\tilde{y}_i$ is used for ID. As a result, after converting the received signal to baseband and performing self-interference cancelation, the obtained signal is denoted as

$$y_i = \sqrt{1-\rho}(\mathbf{g}_i^T\mathbf{W}\mathbf{h}_{\bar{i}}x_{\bar{i}} + \mathbf{g}_i^T\mathbf{x} + \mathbf{g}_i^T\mathbf{W}\tilde{\mathbf{n}}_R + n_{i,d}) + n_{i,c}, \tag{5}$$

where $n_{i,c} \sim \mathcal{CN}(0, \sigma_{i,c}^2)$ is the additive Gaussian noise introduced by the signal conversion from RF band to baseband. Accordingly, the SINR at the node S_i is given by

$$\mathrm{SINR}_i = \frac{P_{\bar{i}}|\mathbf{g}_i^T\mathbf{W}\mathbf{h}_{\bar{i}}|^2}{\mathbf{g}_i^T\mathbf{Q}_x\mathbf{g}_i^* + \sigma_r^2||\mathbf{g}_i^T\mathbf{W}||_2^2 + \sigma_{i,d}^2 + \frac{\sigma_{i,c}^2}{1-\rho}}. \tag{6}$$

Moreover, the other portion of the received signal, $\sqrt{\rho}\tilde{y}_i$, is used for EH. Since the background noise at the EH receiver is negligible and thus can be ignored [6], the harvested energy, E_i during EH time $T/2$ is given by

$$E_i = \frac{\eta T}{2}\rho(|\mathbf{g}_i^T\mathbf{W}\mathbf{h}_{\bar{i}}|^2 P_{\bar{i}} + |\mathbf{g}_i^T\mathbf{W}\mathbf{h}_i|^2 P_i + \mathbf{g}_i^T\mathbf{Q}_x\mathbf{g}_i^*), \tag{7}$$

where η is the energy conversion efficiency with $0 < \eta < 1$ which depends on the rectification process and the EH circuitry [6]. Note that in (7), the self-interference can be used for EH, which is different from ID.

Our design goal is to maximize the weighted sum power at two EH nodes, which is defined as the harvested energy minus the consumed energy. The corresponding optimization problem can be formulated as

$$\begin{aligned}
\max_{P_1,P_2,\rho,\mathbf{W},\mathbf{Q}_x\succeq 0} \quad & \alpha(E_1-\frac{P_1T}{2})+\beta(E_2-\frac{P_2T}{2}) \\
\textit{s.t.} \quad & \mathrm{SINR}_i \geq \tau_i,\ i=1,2, \\
& P_i \leq P_{max,i},\ i=1,2, \\
& \mathrm{Tr}\{\mathbb{E}(\mathbf{x}_R\mathbf{x}_R^H)\} \leq P_r.
\end{aligned} \tag{8}$$

In (8), α and β correspond to the given energy weights for the two EH receivers S_1 and S_2, respectively, where a larger weight value indicates a higher priority of transferring energy to the corresponding EH receiver as compared to other EH receiver. τ_i and $P_{max,i}$ are the minimum SINR requirement and the maximum transmit power at node S_i, respectively.

III. Iterative Optimization Algorithm

This section proposes an iterative algorithm to solve the joint optimization problem (8). Our idea is to optimize a portion of variables when the others are fixed and then search all the potential results to produce the optimal solution [16], [17]. More specifically, in the first step, we try to find the solutions of $\mathbf{W}$ and $\mathbf{Q}_x$ for fixed P_1, P_2 and ρ values. In the second step, we update the values of P_1, P_2 and ρ by fixing the remaining parameters. Finally, we show the iterative optimization algorithm can converge.

1) Optimize $\mathbf{W}$ *and* $\mathbf{Q}_x$ *for fixed* P_1*,* P_2 *and* ρ: Note that when fixing P_1, P_2 and ρ, the problem of optimizing variables $\mathbf{W}$ and $\mathbf{Q}_x$ is equivalent to

$$\begin{aligned}
\max_{\mathbf{W},\mathbf{Q}_x\succeq 0} \quad & \alpha\rho(|\mathbf{g}_1^T\mathbf{W}\mathbf{h}_2|^2P_2+|\mathbf{g}_1^T\mathbf{W}\mathbf{h}_1|^2P_1+\mathbf{g}_1^T\mathbf{Q}_x\mathbf{g}_1^*) \\
& +\beta\rho(|\mathbf{g}_2^T\mathbf{W}\mathbf{h}_1|^2P_1+|\mathbf{g}_2^T\mathbf{W}\mathbf{h}_2|^2P_2+\mathbf{g}_2^T\mathbf{Q}_x\mathbf{g}_2^*) \\
\textit{s.t.} \quad & \mathrm{SINR}_i \geq \tau_i,\ i=1,2. \\
& \mathrm{P}_1||\mathbf{W}\mathbf{h}_1||_2^2+\mathrm{P}_2||\mathbf{W}\mathbf{h}_2||_2^2+\mathrm{Tr}(\mathbf{Q}_x)+\sigma_r^2||\mathbf{W}||_F^2 \leq P_r,
\end{aligned} \tag{9}$$

To find the optimal solution of problem (9), we define a new variable $\mathbf{w}=\mathrm{vec}(\mathbf{W})$, then use the (10) identity

$$\mathrm{Tr}(\mathbf{ABCD})=(\mathrm{vec}(\mathbf{D}^T))^T(\mathbf{C}^T\otimes\mathbf{A})\mathrm{vec}(\mathbf{B}). \tag{10}$$

As a result, we have $|\mathbf{g}_i^T\mathbf{W}\mathbf{h}_i|^2=\mathrm{Tr}((\mathbf{h}_i^*\mathbf{h}_i^T\otimes\mathbf{g}_i^*\mathbf{g}_i^T)\mathbf{w}\mathbf{w}^H)$ and $||\mathbf{W}\mathbf{h}_i||_2^2=\mathrm{Tr}((\mathbf{h}_i^*\mathbf{h}_i^T\otimes\mathbf{I})\mathbf{w}\mathbf{w}^H)$. Then, let $\tilde{\mathbf{W}}\triangleq\mathbf{w}\mathbf{w}^H$, (9) can be rewritten as

$$\begin{aligned}
\max_{\tilde{\mathbf{W}}\succeq 0,\mathbf{Q}_x\succeq 0} \quad & \mathrm{Tr}(\mathbf{A}_1\tilde{\mathbf{W}})+\mathrm{Tr}(\mathbf{B}_1\mathbf{Q}_x) \\
\textit{s.t.} \quad & \mathrm{Tr}(\mathbf{C}_1^i\tilde{\mathbf{W}})-\mathrm{Tr}(\tau_i\mathbf{g}_i^*\mathbf{g}_i^T\mathbf{Q}_x)\geq D_1^i,\ i=1,2. \\
& \mathrm{Tr}(\mathbf{E}_1\tilde{\mathbf{W}})+\mathrm{Tr}(\mathbf{Q}_x)\leq P_r, \\
& \mathrm{Rank}(\tilde{\mathbf{W}})=1.
\end{aligned} \tag{11}$$

where $\mathbf{A}_1 \triangleq (P_2\mathbf{h}_2^*\mathbf{h}_2^T+P_1\mathbf{h}_1^*\mathbf{h}_1^T)\otimes(\alpha\rho\mathbf{g}_1^*\mathbf{g}_1^T+\beta\rho\mathbf{g}_2^*\mathbf{g}_2^T)$, $\mathbf{B}_1 \triangleq (\alpha\rho\mathbf{g}_1^*\mathbf{g}_1^T+\beta\rho\mathbf{g}_2^*\mathbf{g}_2^T)$, $\mathbf{C}_1^i \triangleq (P_{\bar{i}}\mathbf{h}_{\bar{i}}^*\mathbf{h}_{\bar{i}}^T-\tau_i\sigma_r^2I)\otimes\mathbf{g}_i^*\mathbf{g}_i^T$, $D_1^i \triangleq (\sigma_{i,d}^2+\frac{\sigma_{i,c}^2}{1-\rho})\tau_i$, and $\mathbf{E}_1\triangleq(P_1\mathbf{h}_1^*\mathbf{h}_1^T+P_2\mathbf{h}_2^*\mathbf{h}_2^T+\sigma_r^2I)\otimes I$. Due to the rank-one constraint, finding the optimal solution of (11) is difficult. Therefore, we drop the rank-one constraint to construct a semidefinite programming (SDP) problem as follows

$$\begin{aligned}
\max_{\tilde{\mathbf{W}}\succeq 0,\mathbf{Q}_x\succeq 0} \quad & \mathrm{Tr}(\mathbf{A}_1\tilde{\mathbf{W}})+\mathrm{Tr}(\mathbf{B}_1\mathbf{Q}_x) \\
\textit{s.t.} \quad & \mathrm{Tr}(\mathbf{C}_1^i\tilde{\mathbf{W}})-\mathrm{Tr}(\tau_i\mathbf{g}_i^*\mathbf{g}_i^T\mathbf{Q}_x)\geq D_1^i,\ i=1,2. \\
& \mathrm{Tr}(\mathbf{E}_1\tilde{\mathbf{W}})+\mathrm{Tr}(\mathbf{Q}_x)\leq P_r,
\end{aligned} \tag{12}$$

Problem (12) is convex and can be solved by CVX [18]. However, the problem in (12) is equivalent to the problem in (11) only when the problem in (12) has a rank-one optimal solution of $\tilde{\mathbf{W}}$. Consequently, we have the following lemma.

Lemma 1. *The rank-one optimal solution of the problem in* (12) *always exists.*

Proof: The proof is based on [19] and is omitted due to space limitation.

By acquiring the optimal rank-one solution of (12), we can further get the optimal solution of (9).

2) Optimize P_1*,* P_2 *and* ρ *for fixed* $\mathbf{W}$ *and* $\mathbf{Q}_x$: In the second step, we need to optimize the power P_1, P_2 and the power ratio ρ with the remaining variables fixed. The corresponding optimization problem can be formulated as

$$\begin{aligned}
\max_{P_1,P_2,\rho} \quad & \alpha(E_1-\frac{P_1T}{2})+\beta(E_2-\frac{P_2T}{2}) \\
\textit{s.t.} \quad & \mathrm{SINR}_i\geq\tau_i,\ i=1,2. \\
& P_1||\mathbf{W}\mathbf{h}_1||_2^2+P_2||\mathbf{W}\mathbf{h}_2||_2^2+\mathrm{Tr}(\mathbf{Q}_x) \\
& +\sigma_r^2||\mathbf{W}||_F^2\leq P_r, \\
& 0<P_i\leq P_{max,i},\ i=1,2. \\
& 0<\rho<1,
\end{aligned} \tag{13}$$

Similar to problem (9), we apply the above transformations in (13). As a result, the problem of optimizing the variables P_1, P_2 and ρ is equivalent to

$$\max_{P_1,P_2,\rho} \quad A_2\rho P_2+B_2\rho P_1-\alpha P_1-\beta P_2+C_2\rho \tag{14a}$$
$$\textit{s.t.} \quad (E_2P_2-D_2)(1-\rho)\geq\tau_1\sigma_{1,c}^2, \tag{14b}$$
$$(G_2P_1-F_2)(1-\rho)\geq\tau_2\sigma_{2,c}^2, \tag{14c}$$
$$P_1J_2+P_2K_2\leq P_r-L_2, \tag{14d}$$
$$0<P_1\leq P_{max,1}, \tag{14e}$$
$$0<P_2\leq P_{max,2}, \tag{14f}$$
$$0<\rho<1. \tag{14g}$$

Here, $A_2 \triangleq \frac{\alpha\eta T}{2}|\mathbf{g}_1^T\mathbf{W}\mathbf{h}_2|^2+\frac{\beta\eta T}{2}|\mathbf{g}_2^T\mathbf{W}\mathbf{h}_2|^2$, $B_2 \triangleq \frac{\alpha\eta T}{2}|\mathbf{g}_1^T\mathbf{W}\mathbf{h}_1|^2+\frac{\beta\eta T}{2}|\mathbf{g}_2^T\mathbf{W}\mathbf{h}_1|^2$, $C_2 \triangleq \frac{\alpha\eta T}{2}\mathbf{g}_1^T\mathbf{Q}_x\mathbf{g}_1^*+\frac{\beta\eta T}{2}\mathbf{g}_2^T\mathbf{Q}_x\mathbf{g}_2^*$, $D_2 \triangleq (\mathbf{g}_1^T\mathbf{Q}_x\mathbf{g}_1^*+\sigma_r^2||\mathbf{g}_1^T\mathbf{W}||_2^2+\sigma_{1,d}^2)\tau_1$, $E_2\triangleq|\mathbf{g}_1^T\mathbf{W}\mathbf{h}_2|^2$, $F_2\triangleq(\mathbf{g}_2^T\mathbf{Q}_x\mathbf{g}_2^*+\sigma_r^2||\mathbf{g}_2^T\mathbf{W}||_2^2+\sigma_{2,d}^2)\tau_2$, $G_2\triangleq|\mathbf{g}_2^T\mathbf{W}\mathbf{h}_1|^2$, $J_2\triangleq||\mathbf{W}\mathbf{h}_1||_2^2$, $K_2\triangleq||\mathbf{W}\mathbf{h}_2||_2^2$ and $L_2\triangleq\mathrm{Tr}(\mathbf{Q}_x)+\sigma_r^2||\mathbf{W}||_F^2$.

Since the optimization variables P_1, P_2 and ρ are coupled in (14b), (14c) and (14d), problem (14) is still intractable. To find the optimal solution of (14), we give the following lemma.

LEMMA 2. *Let $\{P_1^*, P_2^*, \rho^*\}$ denote an optimal solution of problem (14), we have: (1) for the optimal solution $\{P_1^*, P_2^*, \rho^*\}$, there are at least two constraints of problem (14) are achieved with equality; (2) the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ can be obtained in closed-form by comparing the following eight cases:*

- *When the two SINR constraints* (14b) *and* (14c) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = \frac{\frac{\tau_2\sigma_{2,c}^2}{1-\rho^*} + F_2}{G_2}, \quad P_2^* = \frac{\frac{\tau_1\sigma_{1,c}^2}{1-\rho^*} + D_2}{E_2}, \quad \rho^* = 1 - \sqrt{\frac{a_1 + a_2 - a_3}{a_1}}, \tag{15}$$
where $a_1 \triangleq -(A_2D_2G_2 + B_2E_2F_2 + C_2E_2G_2)$, $a_2 \triangleq A_2E_2\tau_1\sigma_{1,c}^2 + B_2E_2\tau_2\sigma_{2,c}^2 + A_2D_2G_2$ and $a_3 \triangleq \alpha E_2\tau_2\sigma_{2,c}^2 + \beta G_2\tau_1\sigma_{1,c}^2$.
- *When the constraints* (14b) *and* (14d) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = \frac{P_r - L_2 - P_2^*K_2}{J_2}, \quad P_2^* = \frac{\frac{\tau_1\sigma_{1,c}^2}{1-\rho^*} + D_2}{E_2}, \quad \rho^* = 1 - \sqrt{-\frac{b_1 + b_2}{J_2E_2b_3}}, \tag{16}$$
where $b_1 \triangleq (A_2J_2 - B_2K_2)\tau_1\sigma_{1,c}^2$, $b_2 \triangleq (\alpha K_2 - \beta J_2)\tau_1\sigma_{1,c}^2$ and $b_3 \triangleq \frac{(P_rE_2 - L_2E_2 - D_2K_2)B_2 + (A_2D_2 + C_2E_2)J_2}{J_2E_2}$.
- *When the constraints* (14b) *and* (14e) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = P_{max,1}, P_2^* = \frac{\frac{\tau_1\sigma_{1,c}^2}{1-\rho^*} + D_2}{E_2}, \rho^* = 1 - \sqrt{\frac{c_2 - c_1}{E_2c_3}}, \tag{17}$$
where $c_1 \triangleq A_2\tau_1\sigma_{1,c}^2$, $c_2 \triangleq \beta\tau_1\sigma_{1,c}^2$ and $c_3 \triangleq \frac{A_2D_2 + B_2E_2P_{max,1} + C_2E_2}{E_2}$.
- *When the constraints* (14c) *and* (14d) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = \frac{\frac{\tau_2\sigma_{2,c}^2}{1-\rho^*} + F_2}{G_2}, \quad P_2^* = \frac{P_r - L_2 - P_1^*J_2}{K_2}, \quad \rho^* = 1 - \sqrt{-\frac{d_1 + d_2}{K_2G_2d_3}}, \tag{18}$$
where $d_1 \triangleq (B_2K_2 - A_2J_2)\tau_2\sigma_{2,c}^2$, $d_2 \triangleq (\beta J_2 - \alpha K_2)\tau_2\sigma_{2,c}^2$ and $d_3 \triangleq \frac{(P_rG_2 - L_2G_2 - F_2J_2)A_2 + (B_2F_2 + C_2G_2)K_2}{G_2K_2}$.
- *When the constraints* (14c) *and* (14f) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = \frac{\frac{\tau_2\sigma_{2,c}^2}{1-\rho^*} + F_2}{G_2}, P_2^* = P_{max,2}, \rho^* = 1 - \sqrt{\frac{e_2 - e_1}{G_2e_3}}, \tag{19}$$
where $e_1 \triangleq B_2\tau_2\sigma_{2,c}^2$, $e_2 \triangleq \alpha\tau_2\sigma_{2,c}^2$ and $e_3 \triangleq \frac{B_2F_2 + A_2G_2P_{max,2} + C_2G_2}{G_2}$.
- *When the two transmit power constraints* (14d) *and* (14e) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = P_{max,1}, \quad P_2^* = \frac{P_r - L_2 - J_2P_{max,1}}{K_2}, \quad \rho^* = min\{1 - \frac{\tau_1\sigma_{1,c}^2}{E_2P_2^* - D_2}, 1 - \frac{\tau_2\sigma_{2,c}^2}{G_2P_1^* - F_2}\}, \tag{20}$$
- *When the constraints* (14d) *and* (14f) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = \frac{P_r - L_2 - K_2P_{max,2}}{J_2}, \quad P_2^* = P_{max,2}, \quad \rho^* = min\{1 - \frac{\tau_1\sigma_{1,c}^2}{E_2P_2^* - D_2}, 1 - \frac{\tau_2\sigma_{2,c}^2}{G_2P_1^* - F_2}\}, \tag{21}$$
- *When the constraints* (14e) *and* (14f) *hold with equality, the optimal solution $\{P_1^*, P_2^*, \rho^*\}$ are given by*
$$P_1^* = P_{max,1}, \quad P_2^* = P_{max,2}, \quad \rho^* = min\{1 - \frac{\tau_1\sigma_{1,c}^2}{E_2P_2^* - D_2}, 1 - \frac{\tau_2\sigma_{2,c}^2}{G_2P_1^* - F_2}\}. \tag{22}$$

Proof: Due to space limitation, please refer to [20] for the omitted proof of this lemma.

We compare all objective function values by substituting (15)∼(22) into (14a) and select one $\{P_1^*, P_2^*, \rho^*\}$ as the optimal solution, if they lead to the greatest value of the objective function $f(\rho^*)$.

3) Convergence of the Iterative Algorithm

By combining the solution processes in steps *1)* and *2)*, the optimal design for AF strategy can be achieved. For clarity, the detailed procedure of the iterative optimization algorithm is listed in Table I.

LEMMA 3. *The proposed iterative algorithm listed in Table I converges.*

Proof: Since the optimal closed-form solutions $\{\mathbf{W}, \mathbf{Q}_x\}$ and $\{P_1, P_2, \rho\}$ can be obtained separately by steps 4 and 5 in Table I at each iteration, i.e., maximizing the objective function of problem (8), the algorithm in Table I leads to the fact that the weighted sum power E^l is monotonically nondecreasing in the iterating process. Additionally, the constraints of problem (8) are bounded. Hence, the objective function of problem (8) is bounded as well. Therefore, we conclude that the iterative optimization algorithm converges based on the monotonicity and boundedness guarantee [17], [21].

IV. SIMULATION RESULTS

In this section, we numerically evaluate the performance of the proposed energy harvesting scheme. The channel vector $\mathbf{h}_i$ and $\mathbf{g}_i$ are set to be Rayleigh fading. The channel gain is modeled by the distance path loss model [15], given as $g_{i,j} = c \cdot d_{i,j}^{-n}$, where c is an attenuation constant set as 1, n

TABLE I
THE PROPOSED ITERATIVE ALGORITHM

1:	**Set** $L_{max} = 1000$ (maximum number of iterations); $l = 0$; $\varepsilon = 10^{-5}$ (convergence tolerance); $E^l_{diff} = 1000$; $E^l_0 = 0$.
2:	**Initialize** $P_1 = P_{max,1}$, $P_2 = P_{max,2}$ and $\rho = 0.5$.
3:	**While** $E^l_{diff} \geq \varepsilon$ and $l < L_{max}$ do.
4:	Calculate $\mathbf{W}$ and $\mathbf{Q}_x$ of problem (12) by CVX [18], then get the optimal $\{\mathbf{W}, \mathbf{Q}_x\}$ of (9) by using eigenvalue decomposition (EVD).
5:	Calculate P_1, P_2 and ρ of problem (14) by substituting (15)$\sim$(22) into (14a).
6:	Calculate the corresponding E^l_1 and E^l_2 by (7) and let the weighted sum power $E^l = \alpha(E^l_1 - \frac{P_1 T}{2}) + \beta(E^l_2 - \frac{P_2 T}{2})$.
7:	$E^l_{diff} = \lvert E^l_0 - E^l \rvert$.
8:	$E^l_0 = E^l$.
9:	$l = l + 1$.
10:	**Until convergence**.

is the path loss exponent and fixed at 3, and $d_{i,j}$ denotes the distance between nodes i and j. For simplicity, we assume that the noise power at all the destinations are the same, i.e., $\sigma^2_{i,c} = \sigma^2_{i,d} = \sigma^2_r = \sigma^2 = 1$ W, $\forall i$, and $\eta = 50\%$, $T = 1$ s. Moreover, the maximum transmit powers at the two sources, if not specified, are set as $P_{max,1} = P_{max,2} = P_{max} = 1.25$ W. In all simulations, the weighted sum power of the relay network is computed by using 1000 randomly generated channel realizations.

In Fig. 2, we first present the harvested energy for AF relaying strategy at different distance of two sources when the relay node is equipped with $N = 4$ transmit antennas. From simulation results, illustrated in Fig. 2(a), when the distances of the two source nodes are symmetric, we find that if S_1 and S_2 have the same priority, i.e., $\alpha = \beta = 0.5$, the two nodes can achieve a fair energy efficiency. When S_1 and S_2 have different priorities, i.e., $\alpha = 0.8$ and $\beta = 0.2$, node S_1 can harvest more energy since its energy weight factor is set to a larger value. However, it is noted that in asymmetric scenario, in Fig. 2(b), although two source nodes S_1 and S_2 have same priority, the node S_2 still harvests much lower energy. The main reason is that the location of S_2 is far away from the relay node R, which could result in very small channel gain as compared to the near node. This coupled effect is referred to as the doubly-near-far problem [2]. However, when with higher priority, i.e., $\beta = 0.9$, we find that node S_2 can share more energy for the harvested total energy, which can provide an effective solution to the doubly-near-far problem.

Secondly, in Fig. 3, we compare the proposed joint optimization scheme with the other two schemes, i.e., only precoding scheme and only power allocation scheme. From simulation results, we find that the joint optimization scheme achieves the best performance as it uses the degrees of the freedom of both power, PS ratio allocation and precoding. It is worth noting that when the relay transmit power is low, the proposed joint optimization scheme achieves lower the harvested energy than the only power allocation scheme then outperforms the latter as P_r increases. This is because the joint optimization scheme can always use the maximum available relay transmit power to improve the total harvested energy.

Finally, in Figs. 4 and 5, we illustrate the harvested energy for different sources transmit power and the number of antennas at relay. From Fig. 4, we find that the performance of the proposed scheme with $P_{max,1} = P_{max,2} = 2$ W is not outperforms the case with $P_{max,1} = P_{max,2} = 1.25$ W. The main reason is that unlike the relay, two sources need to adjust its transmit power rather than using full power. From Fig. 5,

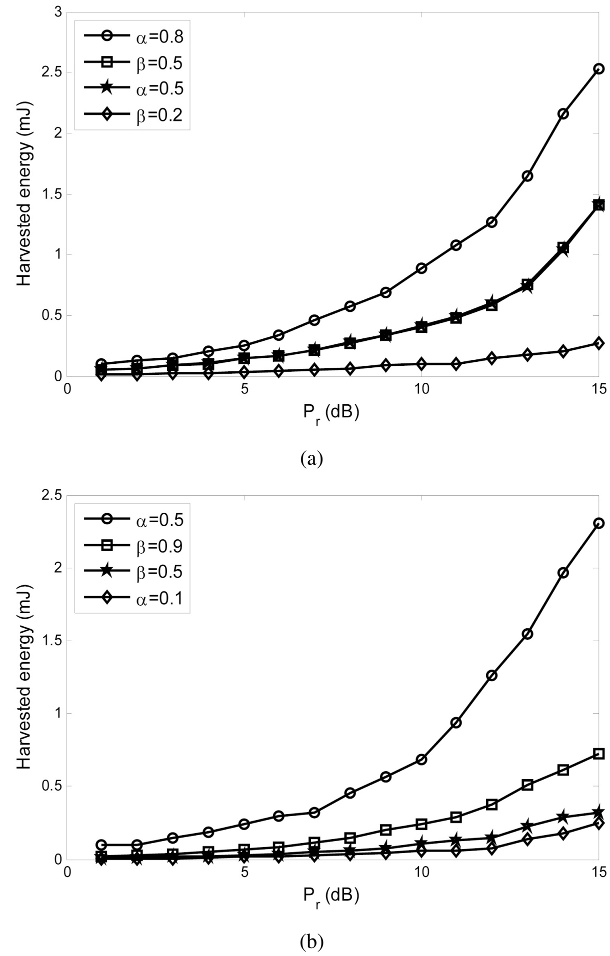

Fig. 2. Performance comparison with different priority at source nodes. (a) Symmetric case, $d_{R,S_1} = d_{R,S_2} = 5$ meters. (b) Asymmetric case, $d_{R,S_1} = 5$ meters and $d_{R,S_2} = 10$ meters.

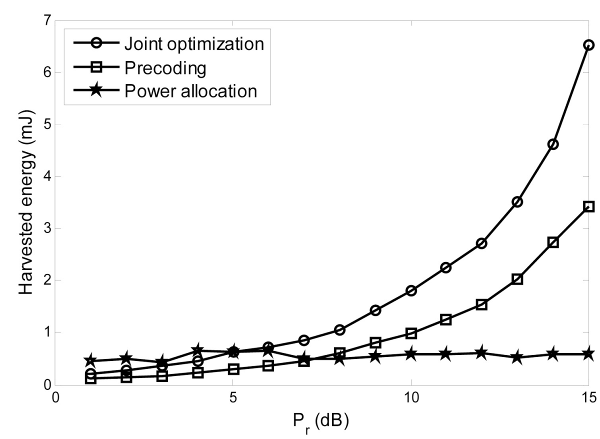

Fig. 3. Performance comparison with different schemes at $\alpha = \beta = 0.5$, $d_{R,S_1} = d_{R,S_2} = 5$ and $N = 4$.

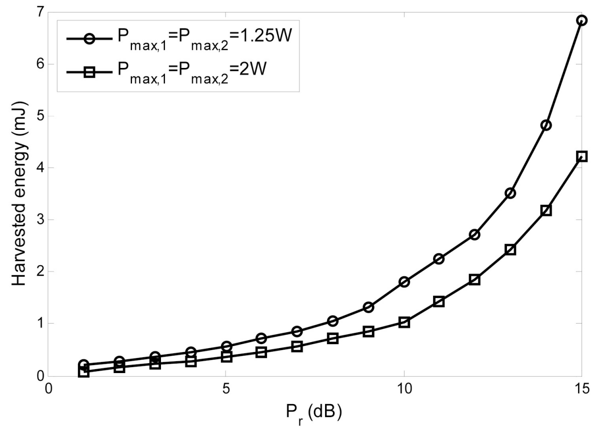

Fig. 4. Performance comparison with different transmit power at sources node with $\alpha = \beta = 0.5$, $d_{R,S_1} = d_{R,S_2} = 5$ and $N = 4$.

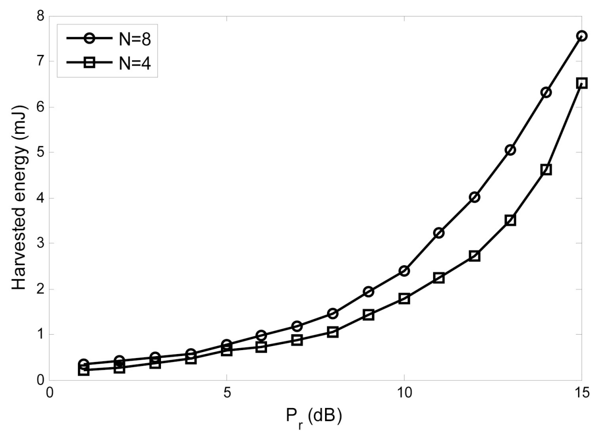

Fig. 5. Performance comparison with different number of antennas at relay node with $\alpha = \beta = 0.5$ and $d_{R,S_1} = d_{R,S_2} = 5$.

we see that when the number of transmit antennas increases ($N = 4 \rightarrow 8$), the harvested energy is substantially increased. This demonstrates the significant benefit by applying large or even massive antenna arrays for efficiently implementing TWR SWIPT systems in practice.

V. Conclusions

This paper has studied the joint beamforming and PS design problem for SWIPT in AF-based TWR network. The weighted sum power at two source nodes was maximized subject to given SINR constraints at source nodes and transmitted power constraints at relay node. Considering the AF relaying strategy, the design problem is formulated as nonconvex quadratically constrained problem, which is decoupled into two subproblems that can be solved separately by applying suitable optimization tools. The performance was compared and some practical implementation issues were discussed. Numerical results verified the effectiveness of the proposed jointly designs.

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