T. T. Dat Nguyen and J. Yu, "RTS Smoother for GLMB filter," 2019 International Conference on Control, Automation and Information Sciences (ICCAIS), Chengdu, China, 2019, pp. 1-6, doi: 10.1109/ICCAIS46528.2019.9074579.

Joint Source and Relay Design for Wireless Powered AF MIMO Relay Systems with Direct Link

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***Abstract*—In this paper, we consider a dual-hop amplify-and-forward (AF) multiple-input multiple-output (MIMO) relay system with a wireless powered relay node. In particular, the time switching (TS) protocol is applied between wireless information and energy transfer at the relay node. The direct link between the source and destination nodes is considered. We study the joint optimization of the source and relay precoding matrices and the TS factor to maximize the source-destination mutual information (MI) when a single data stream is transmitted from the source node. We derive the optimal structure of the source and relay precoding matrices, which reduces the original problem to a simpler optimization problem. The simplified problem is then solved efficiently by a two-step method. Numerical simulations show that the proposed algorithm yields a higher MI and better rate-energy tradeoff than approaches with a fixed TS factor.**

I. Introduction

Traditional wireless devices are powered by batteries with a limited life time. A high cost is usually associated with replacing batteries to extend the life time of wireless devices. Furthermore, due to the physical and economic constraints, replacing batteries cannot be easily carried out in many real scenarios in practice. Wireless power transfer techniques, which have the potential to avoid replacing batteries, have received increasing interests recently [1].

The concept of simultaneous wireless information and energy transfer has been proposed in [2], where a receiver is capable of performing information decoding (ID) and energy harvesting (EH) simultaneously. To coordinate wireless information transfer and wireless energy transfer in practical systems, a time switching (TS) protocol and a power splitting (PS) protocol have been proposed in [3].

It is well-known that both multiple-input multiple-output (MIMO) and relay communication techniques can improve the system coverage and energy efficiency [4]-[6]. By equipping multiple antennas at wireless devices, radio frequency (RF) energy can be focused on particular devices so that they can be charged more efficiently compared with using a single antenna. The application of EH in MIMO relay systems has been studied in [7]-[11]. In [7], performance trade-offs of several receiver architectures have been discussed by applying EH in MIMO relay systems. Precoder design for decode-and-forward (DF)-based MIMO relay networks has been studied in [8] and [9].

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A TS protocol and a PS protocol have been developed in [10] for an amplify-and-forward (AF) MIMO relay system, where the achievable rate is maximized for each protocol by jointly optimizing the source and relay precoding matrices. In [11], an orthogonal space-time block code (OSTBC) based AF-MIMO relay system with a multi-antenna EH receiver has been investigated.

In this paper, we consider a two-hop AF MIMO relay system with a wireless powered relay node. Different to existing works, we consider the direct link in this paper. The TS protocol is adopted during the source phase, where the source node transfers energy and information signals to the relay node during the first and second time intervals, respectively. During the second time interval, the source node also sends signal to the destination node through the direct link. Then, during the relay phase, the relay node uses the harvested energy to forward the received information to the destination node. As a novel contribution of this paper, we propose an energy consumption constraint at the source node during the information and energy transfer, which is more general than the constant power constraints in [10].

We study the joint optimization of the source precoding matrices, the relay amplifying matrix, and the TS factor to maximize the source-destination mutual information (MI), subjecting to the harvested energy constraint at the relay node and the proposed source energy constraint at the source node. The optimal structure of the source and relay matrices is derived, which reduces the original problem to a simpler problem. Based on the observation that the system MI is a unimodal function of the TS factor, we develop a two-step method to efficiently solve the simplified problem.

In particular, we show that the optimal TS factor can be

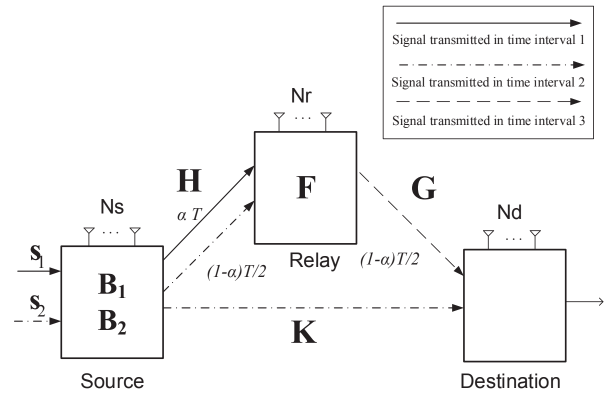

Fig. 1. A dual-hop MIMO relay communication system with direct link and an energy-harvesting relay node.

efficiently found by a golden section search. Whereas for a given TS factor, the subproblem is solved through solving two nonlinear equations in the second step. Numerical simulations show that the proposed algorithm yields a higher MI and better rate-energy tradeoff than approaches with a fixed TS factor.

II. System Model

We consider a three-node two-hop MIMO communication system where the source node transmits information to the destination node with the aid of one relay node as shown in Fig. 1. The source, relay, and destination nodes are equipped with N_s, N_r, and N_d antennas, respectively. We assume that the source node has its own power supply, while the relay node is powered by harvesting the RF energy sent from the source node.

In this paper, a time switching protocol [3] is considered. In particular, there are three intervals in one communication cycle T. In the first time interval, energy is transferred from the source node to the relay node with a duration of αT, where $0 < \alpha < 1$ denotes the time switching factor. In the second time interval, information signals are transmitted from the source node to the relay node with a duration of $(1-\alpha)T/2$. Meanwhile, these signals are also transmitted to the destination node via the direct link. The last time interval of $(1-\alpha)T/2$ is used for relaying the information signals received by the relay node to the destination node. For the simplicity of presentation, we set $T=1$ hereafter. In all three time intervals, signals are linearly precoded before transmission.

More specifically, in the first time interval, an $N_1 \times 1$ energy-carrying signal vector $\mathbf{s}_1(t)$ is precoded by an $N_s \times N_1$ matrix $\mathbf{B}_1$ at the source node and transmitted to the relay node. We assume that $E\{\mathbf{s}_1(t)\mathbf{s}_1^H(t)\} = \mathbf{I}_{N_1}$, where $E\{\cdot\}$ stands for the statistical expectation, $\mathbf{I}_n$ is an $n \times n$ identity matrix, and $(\cdot)^H$ denotes the Hermitian transpose. The received signal vector at the relay node is given by

$$\mathbf{y}_r(t) = \mathbf{H}\mathbf{B}_1\mathbf{s}_1(t) + \mathbf{v}_r(t), \quad 0 \le t \le \alpha \tag{1}$$

where $\mathbf{H}$ is an $N_r \times N_s$ MIMO channel matrix between the source and relay nodes, $\mathbf{y}_r(t)$ and $\mathbf{v}_r(t)$ are the received signal and the additive Gaussian noise vectors at the relay node, respectively. Based on [3], the RF energy harvested at the relay node is proportional to the baseband received signal in (1), which is given by

$$E_r = \eta\alpha \operatorname{tr}(\mathbf{H}\mathbf{B}_1\mathbf{B}_1^H\mathbf{H}^H) \tag{2}$$

where $\operatorname{tr}(\cdot)$ denotes the matrix trace and $0 < \eta \le 1$ is the energy conversion efficiency.

During the second time interval, an information-bearing signal $s_2(t)$ with $E\{|s_2(t)|^2\} = 1$ is precoded by an $N_s \times 1$ vector $\mathbf{b}_2$ at the source node and transmitted to the relay node. The received signal vector at the relay node can be written as

$$\mathbf{y}_r(t) = \mathbf{H}\mathbf{b}_2 s_2(t) + \mathbf{v}_r(t), \quad \alpha \le t \le \frac{1+\alpha}{2}. \tag{3}$$

While the received signal vector at the destination node in this time interval can be written as

$$\mathbf{y}_d(t) = \mathbf{K}\mathbf{b}_2 s_2(t) + \mathbf{v}_d(t), \quad \alpha \le t \le \frac{1+\alpha}{2} \tag{4}$$

where $\mathbf{K}$ is an $N_d \times N_s$ channel matrix between the source and destination nodes, $\mathbf{y}_d(t)$ and $\mathbf{v}_d(t)$ are the received signal and the additive Gaussian noise vectors at the destination node in the second time interval, respectively.

Finally, during the third time interval, the relay node linearly precodes $\mathbf{y}_r(t)$, $\alpha \le t \le \frac{1+\alpha}{2}$, with an $N_r \times N_r$ matrix $\mathbf{F}$ and transmits the precoded signal vector

$$\mathbf{x}_r(t) = \mathbf{F}\mathbf{y}_r\Big(t - \frac{1-\alpha}{2}\Big), \quad \frac{1+\alpha}{2} \le t \le 1 \tag{5}$$

to the destination node. From (3) and (5), the received signal vector at the destination node in the third time interval can be written as

$$\begin{aligned}\mathbf{y}_d(t) &= \mathbf{G}\mathbf{x}_r(t) + \mathbf{v}_d(t)\\ &= \mathbf{G}\mathbf{F}\mathbf{H}\mathbf{b}_2 s_2\Big(t - \frac{1-\alpha}{2}\Big) + \mathbf{G}\mathbf{F}\mathbf{v}_r\Big(t - \frac{1-\alpha}{2}\Big)\\ &\quad + \mathbf{v}_d(t), \quad \frac{1+\alpha}{2} \le t \le 1\end{aligned} \tag{6}$$

where $\mathbf{G}$ is an $N_d \times N_r$ MIMO channel matrix between the relay and destination nodes, $\mathbf{y}_d(t)$ and $\mathbf{v}_d(t)$ are the received signal vector at the third time interval and the additive Gaussian noise vector at the destination node, respectively. Combining (4) and (6), the received signal vector at the destination over the second and the third time intervals is

$$\begin{aligned}\mathbf{y} &\triangleq \begin{bmatrix}\mathbf{y}_d(t)\\ \mathbf{y}_d\big(t - \frac{1-\alpha}{2}\big)\end{bmatrix}\\ &= \begin{bmatrix}\mathbf{G}\mathbf{F}\mathbf{H}\\ \mathbf{K}\end{bmatrix}\mathbf{b}_2 s_2\Big(t - \frac{1-\alpha}{2}\Big)\\ &\quad + \begin{bmatrix}\mathbf{G}\mathbf{F}\mathbf{v}_r\big(t - \frac{1-\alpha}{2}\big) + \mathbf{v}_d(t)\\ \mathbf{v}_d\big(t - \frac{1-\alpha}{2}\big)\end{bmatrix}, \quad \frac{1+\alpha}{2} \le t \le 1.\end{aligned} \tag{7}$$

From (7), the mutual information between source and destination is given as [12]

$$\mathrm{MI}(\alpha,\mathbf{b}_2,\mathbf{F})=\frac{1-\alpha}{2}\log_2(1+\mathbf{b}_2^H\mathbf{K}^H\mathbf{K}\mathbf{b}_2+\mathbf{b}_2^H\mathbf{H}^H\mathbf{F}^H\mathbf{G}^H \times(\mathbf{G}\mathbf{F}\mathbf{F}^H\mathbf{G}^H+\mathbf{I}_{N_d})^{-1}\mathbf{G}\mathbf{F}\mathbf{H}\mathbf{b}_2) \tag{8}$$

where $(\cdot)^{-1}$ denotes the matrix inversion.

We assume that $\mathbf{H}$, $\mathbf{G}$, and $\mathbf{K}$ are quasi-static and known at the relay node. All noises are assumed to be additive white Gaussian noise (AWGN) with zero-mean and unit-variance. Note that the energy used to transmit $\mathbf{s}_1(t)$ and $s_2(t)$ from the source node is $\alpha\mathrm{tr}(\mathbf{B}_1\mathbf{B}_1^H)$ and $\frac{1-\alpha}{2}\mathbf{b}_2^H\mathbf{b}_2$, respectively. Therefore, the constraint on the energy consumed by the source node can be written as

$$\alpha\mathrm{tr}(\mathbf{B}_1\mathbf{B}_1^H)+\frac{1-\alpha}{2}\mathbf{b}_2^H\mathbf{b}_2\le\frac{1+\alpha}{2}P_s \tag{9}$$

where P_s is the nominal (average) power available at the source node.

From (1) and (5), the energy consumed by the relay node to transmit $\mathbf{x}_r(t)$ to the destination node is given by

$$\frac{1-\alpha}{2}\mathrm{tr}(E\{\mathbf{x}_r(t)\mathbf{x}_r^H(t)\}) =\frac{1-\alpha}{2}\mathrm{tr}(\mathbf{F}(\mathbf{H}\mathbf{b}_2\mathbf{b}_2^H\mathbf{H}^H+\mathbf{I}_{N_r})\mathbf{F}^H). \tag{10}$$

Based on (2) and (10), we obtain the following energy constraint at the relay node

$$\frac{1-\alpha}{2}\mathrm{tr}(\mathbf{F}(\mathbf{H}\mathbf{b}_2\mathbf{b}_2^H\mathbf{H}^H+\mathbf{I}_{N_r})\mathbf{F}^H)\le\alpha\eta\mathrm{tr}(\mathbf{H}\mathbf{B}_1\mathbf{B}_1^H\mathbf{H}^H). \tag{11}$$

From (8), (9), (11), the transceiver optimization problem for linear non-regenerative wireless information and energy transfer MIMO relay systems can be written as

$$\max_{0<\alpha<1,\mathbf{B}_1,\mathbf{b}_2,\mathbf{F}}\ \mathrm{MI}(\alpha,\mathbf{b}_2,\mathbf{F}) \tag{12}$$

$$\text{s.t. }\ \alpha\mathrm{tr}(\mathbf{B}_1\mathbf{B}_1^H)+\frac{1-\alpha}{2}\mathbf{b}_2^H\mathbf{b}_2\le\frac{1+\alpha}{2}P_s \tag{13}$$

$$\mathrm{tr}(\mathbf{F}(\mathbf{H}\mathbf{b}_2\mathbf{b}_2^H\mathbf{H}^H+\mathbf{I}_{N_r})\mathbf{F}^H)\le\frac{2\alpha\eta}{1-\alpha}\mathrm{tr}(\mathbf{H}\mathbf{B}_1\mathbf{B}_1^H\mathbf{H}^H). \tag{14}$$

III. The Proposed Algorithm

The problem (12)-(14) is nonconvex with matrix variables and is challenging to solve. In this section, we develop a novel algorithm to solve the problem (12)-(14). First, we derive the optimal structure of $\mathbf{B}_1$ and $\mathbf{F}$, under which the problem (12)-(14) can be simplified. Let us introduce

$$\mathbf{H}=\mathbf{U}_h\mathbf{\Lambda}_h^{\frac{1}{2}}\mathbf{V}_h^H,\quad \mathbf{G}=\mathbf{U}_g\mathbf{\Lambda}_g^{\frac{1}{2}}\mathbf{V}_g^H \tag{15}$$

as the singular value decompositions (SVDs) of $\mathbf{H}$ and $\mathbf{G}$, respectively, with the diagonal elements of $\mathbf{\Lambda}_h$ and $\mathbf{\Lambda}_g$ sorted in decreasing order.

THEOREM 1: The optimal $\mathbf{B}_1$ and $\mathbf{F}$ as the solution to the problem (12)-(14) has the following structure

$$\mathbf{B}_1^*=\lambda_b^{\frac{1}{2}}\mathbf{v}_{h,1},\quad \mathbf{F}^*=c^{\frac{1}{2}}\mathbf{v}_{g,1}\mathbf{b}_2^H\mathbf{H}^H \tag{16}$$

where $(\cdot)^*$ denotes the optimal value, λ_b and c are positive scalars that remain to be optimized, $\mathbf{v}_{h,1}$ and $\mathbf{v}_{g,1}$ are the first columns of $\mathbf{V}_h$ and $\mathbf{V}_g$, respectively.

Based on Theorem 1, the matrix optimization problem (12)-(14) can be reduced to a simpler problem. This can be done by substituting (16) back into (12)-(14), and we have

$$\max_{\alpha,\mathbf{b}_2,c,\lambda_b}\ \frac{1-\alpha}{2}\log_2\left(1+\|\mathbf{K}\mathbf{b}_2\|^2+\frac{\|\mathbf{H}\mathbf{b}_2\|^2}{1+(c\lambda_{g,1}\|\mathbf{H}\mathbf{b}_2\|^2)^{-1}}\right) \tag{17}$$

$$\text{s.t. }\ \alpha\lambda_b+\frac{1-\alpha}{2}\|\mathbf{b}_2\|^2\le\frac{1+\alpha}{2}P_s \tag{18}$$

$$c(\|\mathbf{H}\mathbf{b}_2\|^4+\|\mathbf{H}\mathbf{b}_2\|^2)\le\frac{2\alpha\eta}{1-\alpha}\lambda_{h,1}\lambda_b \tag{19}$$

where $\|\cdot\|$ stands for the vector Euclidian norm and $\lambda_{h,1}$ denotes the first diagonal element of $\mathbf{\Lambda}_h$. As (17) monotonically increases with $\|\mathbf{H}\mathbf{b}_2\|^2$, for any λ_b, the optimal $\mathbf{b}_2$ maximizing (17) must satisfy equality in the constraint (19), i.e.,

$$\alpha\lambda_b=\frac{(1-\alpha)c}{2\eta\lambda_{h,1}}(\|\mathbf{H}\mathbf{b}_2\|^4+\|\mathbf{H}\mathbf{b}_2\|^2). \tag{20}$$

By substituting (20) back into (18), the problem (17)-(19) can be equivalently rewritten as

$$\max_{\alpha,\mathbf{b}_2,c}\ \frac{1-\alpha}{2}\log_2\left(1+\|\mathbf{K}\mathbf{b}_2\|^2+\frac{\|\mathbf{H}\mathbf{b}_2\|^2}{1+(c\lambda_{g,1}\|\mathbf{H}\mathbf{b}_2\|^2)^{-1}}\right) \tag{21}$$

$$\text{s.t. }\ \frac{c}{\eta\lambda_{h,1}}(\|\mathbf{H}\mathbf{b}_2\|^4+\|\mathbf{H}\mathbf{b}_2\|^2)+\|\mathbf{b}_2\|^2\le P_s\frac{1+\alpha}{1-\alpha}. \tag{22}$$

To proceed further, we define $M(\alpha)$ as the optimal value of the following problem for a given α

$$\max_{\mathbf{b}_2,c}\ \log_2\left(1+\|\mathbf{K}\mathbf{b}_2\|^2+\frac{\|\mathbf{H}\mathbf{b}_2\|^2}{1+(c\lambda_{g,1}\|\mathbf{H}\mathbf{b}_2\|^2)^{-1}}\right) \tag{23}$$

$$\text{s.t. }\ \frac{c}{\eta\lambda_{h,1}}(\|\mathbf{H}\mathbf{b}_2\|^4+\|\mathbf{H}\mathbf{b}_2\|^2)+\|\mathbf{b}_2\|^2\le P_\alpha \tag{24}$$

where $P_\alpha=P_s\frac{1+\alpha}{1-\alpha}$. Then, the optimal value of the problem (21)-(22) can be written as

$$F(\alpha)=\frac{1-\alpha}{2}M(\alpha). \tag{25}$$

The unimodality of $F(\alpha)$ is difficult to prove rigorously, and it will be illustrated graphically later in this section. Based on this observation, the problem (21)-(22) can be efficiently solved by a two-step algorithm, where for a given α we optimize $\mathbf{b}_2$ and c by solving the problem (23)-(24). And then a simple one dimensional search (such as the golden section search method [13]) can be applied to obtain the optimal α.

As (23) monotonically increases with c, for any $\|\mathbf{b}_2\|^2\le P_\alpha$, the optimal c maximizing (23) must satisfy equality in (24), i.e.,

$$c\|\mathbf{H}\mathbf{b}_2\|^2=\frac{\eta\lambda_{h,1}(P_\alpha-\|\mathbf{b}_2\|^2)}{\|\mathbf{H}\mathbf{b}_2\|^2+1}. \tag{26}$$

Substituting (26) back into (23), the problem (23)-(24) can be equivalently written as

$$\max_{\|\mathbf{b}_2\|^2\le P_\alpha}\ \|\mathbf{K}\mathbf{b}_2\|^2+\frac{\lambda(P_\alpha-\|\mathbf{b}_2\|^2)\,\|\mathbf{H}\mathbf{b}_2\|^2}{\|\mathbf{H}\mathbf{b}_2\|^2+\lambda(P_\alpha-\|\mathbf{b}_2\|^2)+1} \tag{27}$$

where $\lambda = \eta\lambda_{h,1}\lambda_{g,1}$. By introducing new variables x and y with $\lambda(P_\alpha - \|\mathbf{b}_2\|^2) \geq x$ and $\|\mathbf{H}\mathbf{b}_2\|^2 \geq y$, the problem (27) can be converted to

$$\max_{x,y,\mathbf{b}_2} \|\mathbf{K}\mathbf{b}_2\|^2 + \frac{xy}{x+y+1} \tag{28}$$
$$\text{s.t. } \|\mathbf{H}\mathbf{b}_2\|^2 \geq y \tag{29}$$
$$\|\mathbf{b}_2\|^2 \leq P_\alpha - x/\lambda. \tag{30}$$

The problem (28)-(30) can be solved by the Lagrange multiplier method. The corresponding Lagrangian function is given by

$$\mathcal{L} = -\|\mathbf{K}\mathbf{b}_2\|^2 - \frac{xy}{x+y+1} + \beta(y - \|\mathbf{H}\mathbf{b}_2\|^2) + \gamma(\|\mathbf{b}_2\|^2 - P_\alpha + x/\lambda) \tag{31}$$

where $\beta \geq 0$ and $\gamma \geq 0$ are the Lagrange multipliers. Based on the Karush-Kuhn-Tucker (KKT) optimality conditions, we obtain from (31) that

$$\frac{\partial\mathcal{L}}{\partial\mathbf{b}_2} = -\mathbf{b}_2^H\mathbf{K}^H\mathbf{K} - \beta\mathbf{b}_2^H\mathbf{H}^H\mathbf{H} + \gamma\mathbf{b}_2^H = 0 \tag{32}$$
$$\frac{\partial\mathcal{L}}{\partial x} = -\frac{y(y+1)}{(x+y+1)^2} + \frac{\gamma}{\lambda} = 0 \tag{33}$$
$$\frac{\partial\mathcal{L}}{\partial y} = -\frac{x(x+1)}{(x+y+1)^2} + \beta = 0. \tag{34}$$

From (32), we have

$$(\beta\mathbf{H}^H\mathbf{H} + \mathbf{K}^H\mathbf{K})\mathbf{b}_2 = \gamma\mathbf{b}_2. \tag{35}$$

This indicates that the optimal $\mathbf{b}_2$ is

$$\mathbf{b}_2^* = \sqrt{\xi^*}\mathbf{v}(\beta^*\mathbf{H}^H\mathbf{H} + \mathbf{K}^H\mathbf{K}) \tag{36}$$

where ξ^* is a positive scalar, $\mathbf{v}(\mathbf{A})$ stands for the principal eigenvector of matrix $\mathbf{A}$ with $\|\mathbf{v}(\mathbf{A})\| = 1$. For the simplicity of notations, we denote $\mathbf{b}_2^* = \sqrt{\xi^*}\mathbf{v}(\beta^*)$. From (35), the optimal γ is $\gamma^* = e(\beta^*\mathbf{H}^H\mathbf{H} + \mathbf{K}^H\mathbf{K})$, where $e(\mathbf{A})$ stands for the principal eigenvalue of matrix $\mathbf{A}$. Similarly, we denote $\gamma^* = e(\beta^*)$ for the simplicity of notations.

As (28) monotonically increases with $x > 0$ and $y > 0$, to maximize (28), equalities in (29) and (30) must hold at the optimal solution. Therefore, we have

$$y^* = \xi^*\|\mathbf{H}\mathbf{v}(\beta^*)\|^2, \qquad x^* = \lambda(P_\alpha - \xi^*). \tag{37}$$

The rest of the problem is to find β^* and ξ^*. This can be done by substituting (37) back into (33) and (34) and solving the following system of two nonlinear equations

$$\beta^* = \frac{\lambda(P_\alpha - \xi^*)(\lambda(P_\alpha - \xi^*) + 1)}{(\lambda(P_\alpha - \xi^*) + \xi^*\|\mathbf{H}\mathbf{v}(\beta^*)\|^2 + 1)^2} \tag{38}$$
$$\frac{e(\beta^*)}{\lambda} = \frac{\xi^*\|\mathbf{H}\mathbf{v}(\beta^*)\|^2(\xi^*\|\mathbf{H}\mathbf{v}(\beta^*)\|^2 + 1)}{(\lambda(P_\alpha - \xi^*) + \xi^*\|\mathbf{H}\mathbf{v}(\beta^*)\|^2 + 1)^2}. \tag{39}$$

As (38)-(39) are two-dimensional nonlinear equations of β^* and ξ^*, they can be efficiently solved by using standard software package via, for example, the Newton's method, the Broyden's method (quasi-Newton method), and the gradient method [13].

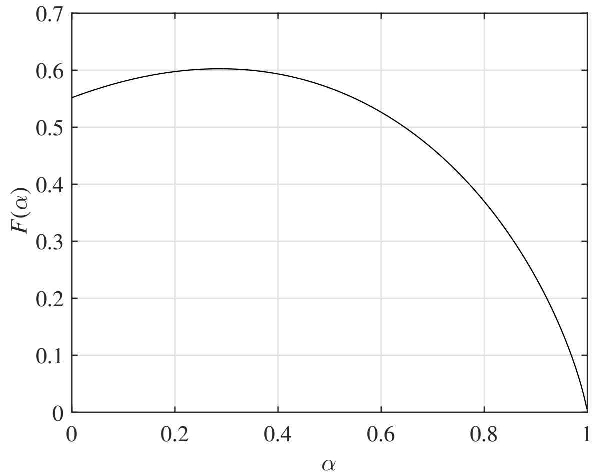

Fig. 2. Unimodality of $F(\alpha)$. $P_s = 5$dB and $N = 3$.

To verify the unimodality of $F(\alpha)$ in (25), we solve the problem (21)-(22) using the proposed algorithm to calculate $F(\alpha)$ numerically. We set $P_s = 5$dB and $N_s = N_r = N_d = N$. Fig. 2 shows $F(\alpha)$ versus α with $N = 3$. It can be seen that $F(\alpha)$ indeed is a unimodal function of α.

IV. SIMULATIONS

In this section, we study the performance of the proposed algorithm via numerical simulations. In the simulations, the three nodes are located in a line, where the distance between the source node and the destination node is 2 meters, and the distance between the source node and the relay node is d. Therefore, the relay-destination distance is $2 - d$. The channel matrices $\mathbf{H}$, $\mathbf{G}$, and $\mathbf{K}$ have complex Gaussian entries with zero-mean and variances $1/d^3$, $1/(2-d)^3$, and $1/2^3$, respectively. For all simulation examples, we fix $\eta = 0.8$ and $N_s = N_r = N_d = N$. We compare the performance of the proposed algorithm with the fixed α algorithm, where $\alpha = 0.3$, $\alpha = 0.5$, and $\alpha = 0.8$. All the numerical simulation results are averaged over 1000 independent channel realizations.

In the first example, we set $d = 1$. The MI of the proposed algorithm and the fixed α approach versus the nominal power P_s for $N = 3$ is shown in Fig. 3. We observe that the proposed algorithm performs better than the fixed α scheme. This is because α is optimized in our proposed algorithm so that a higher MI is obtained.

To further interpret the performance gain of the proposed algorithm in the first example, we plot the optimal time switching factor α calculated by the proposed algorithm in the second example. In this example, we set $d = 1$. Fig. 4 shows the optimal α versus the nominal power P_s with $N = 3$. It can be seen from Fig. 4 that for the proposed algorithm, the optimal α monotonically decreases as the nominal power P_s increases. In particular, the optimal α becomes very small when P_s is above 10dB. The reason is that when P_s is large enough, λ_b (the power level at the source node at the first interval) obtained by the proposed algorithm increases. Thus,

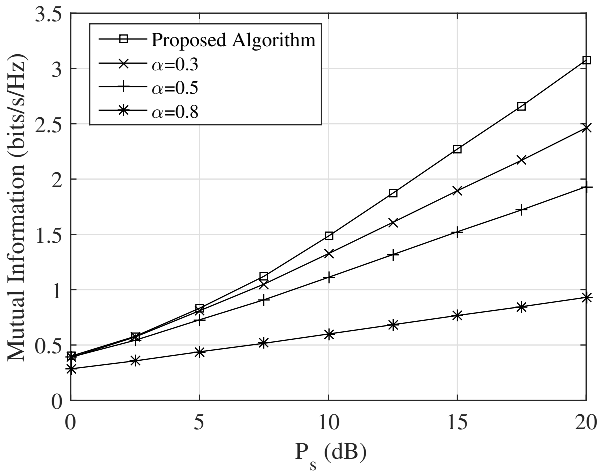

Fig. 3. Example 1: MI versus P_s with $d = 1$ and $N = 3$.

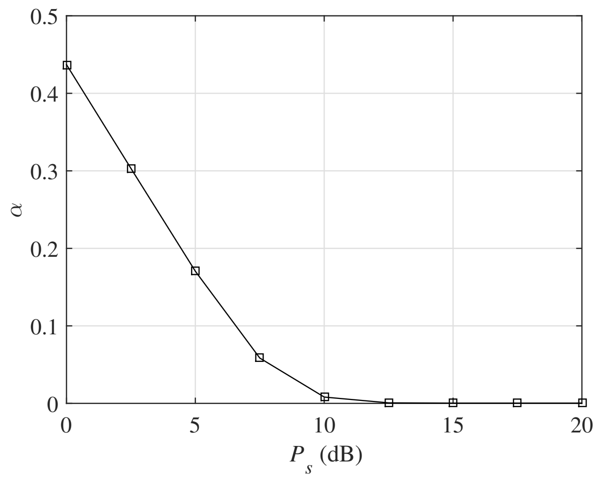

Fig. 4. Example 2: Optimal α versus P_s with $d = 1$ and $N = 3$.

even though α is small, the energy $\alpha\eta\lambda_{h,1}\lambda_b$ harvested by the relay node is sufficient to forward the signal to the destination node. Therefore, more time can be allocated for information transmission so that a higher data rate can be achieved at large P_s.

In the third example, we fix $d = 1$ and study the energy consumption and rate-energy trade-off of the proposed algorithm. We first plot the energy consumption versus P_s with $N = 3$ in Fig. 5. Then, we fix $P_s = 10$dB and plot the MI versus energy with $N = 3$ in Fig. 6. As shown in Fig. 5, the energy cost for the proposed algorithm is lower than any fixed α schemes. The better rate-energy trade-off achieved by the proposed algorithm is demonstrated in Fig. 6. This indicates that the proposed algorithm achieves a higher rate with a less energy consumption through optimizing α.

V. Conclusions

An optimal TS protocol for wireless powered dual-hop AF MIMO relay networks with direct link has been developed

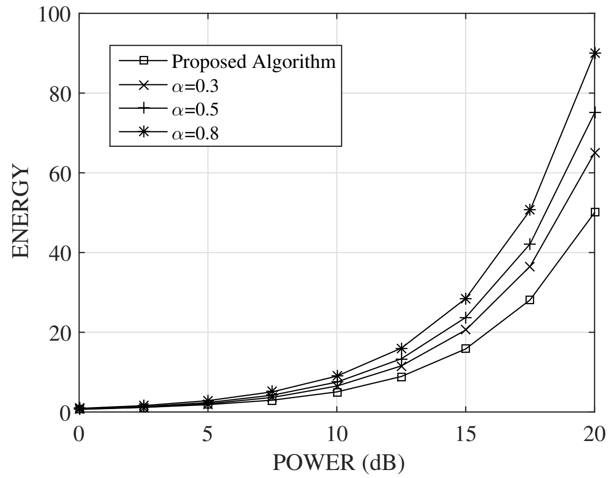

Fig. 5. Energy consumption versus P_s with $N = 3$.

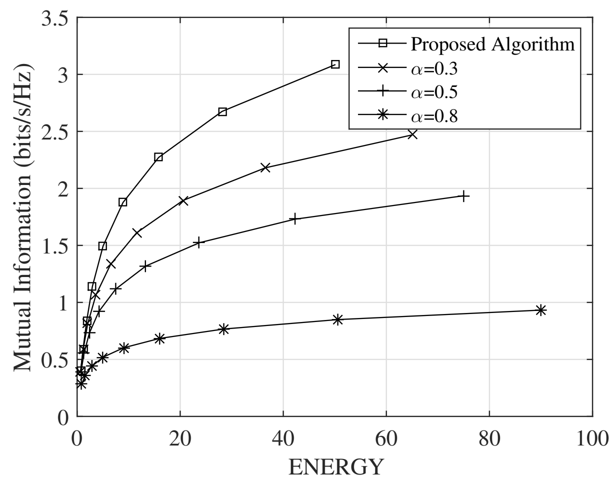

Fig. 6. MI versus energy with $N = 3$.

in this paper. The joint optimization of the source and relay precoding matrices and the TS factor is studied to maximize the source-destination MI subjecting to an energy constraint at the source node and an EH constraint at the relay node. The optimal structure of the source and relay precoding matrices has been derived, which reduces the original problem to a simpler problem. We have shown that this simplified problem is a unimodal function of the TS factor, and a two-step method has been developed to solve this problem. The optimal TS factor has been obtained by the golden section search method. For a given TS factor, the remaining variables are optimized via solving two nonlinear equations by exploring the structure of the problem. Numerical studies show that the proposed algorithm performs better than approaches without optimizing the TS factor.

References

[1] X. Lu, D. Niyato, P. Wang, D. I. Kim, and Z. Han, "Wireless charger networking for mobile devices: Fundamentals, standards, and applica-

tions," *IEEE Wireless Commun.*, vol. 22, pp. 126-135, Apr. 2015.
[2] L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, Toronto, Canada, July 6-11, 2008, pp. 1612-1616.
[3] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, pp. 1989-2001, May 2013.
[4] B. Li, Y. Rong, J. Sun, and K. L. Teo, "A distributionally robust linear receiver design for multi-access space-time block coded MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 16, pp. 464-474, Jan. 2017.
[5] Z. He, J. Zhang, W. Liu, and Y. Rong, "New results on transceiver design for two-hop amplify-and-forward MIMO relay systems with direct link," *IEEE Trans. Signal Process.*, vol. 64, pp. 5232-5241, Oct. 2016.
[6] Y. Rong and M. R. A. Khandaker, "On uplink-downlink duality of multi-hop MIMO relay channel," *IEEE Trans. Wireless Commun.*, vol. 10, pp. 1923-1931, June 2011.
[7] Z. Ding, C. Zhong, D. W. K. Ng, M. Peng, H. A. Suraweera, R. Schober, and H. V. Poor, "Applications of smart antenna technologies in simultaneous wireless information and power transfer," *IEEE Commun. Mag.,* vol. 53, pp. 86-93, Apr. 2015.
[8] B. Fang, W. Zhong, S. Jin, Z. Qian, and W. Shao, "Game-theoretic precoding for SWIPT in the DF-based MIMO relay networks," *IEEE Trans. Veh. Technol.*, vol. 65, pp. 6940-6948, Sep. 2016.
[9] J. Huang, H. Chen, Y. Jiang, J. Meng, A. Xu, X. Guo, and B. Chen, "Precoder design for MIMO decode-and-forward relay channels with energy harvesting constraint," in *Proc. IEEE Conf. Industrial Electronics Applications*, Hefei, China, June 5-7, 2016, pp. 368-372.
[10] K. Xiong, P. Fan, C. Zhang, and K. B. Letaief, "Wireless information and energy transfer for two-hop non-regenerative MIMO-OFDM relay networks," *IEEE J. Select. Areas Commun.*, vol. 26, pp. 1397-1407, Aug. 2015.
[11] B. K. Chalise, W. K. Ma, Y. D. Zhang, H. Suraweera, and M. G. Amin, "Optimum performance boundaries of OSTBC based AF-MIMO relay system with energy harvesting receiver," *IEEE Trans. Signal Process.*, vol. 61, pp. 4199-4213, Sep. 2013.
[12] Y. Rong, "Optimal joint source and relay beamforming for MIMO relays with direct link," *IEEE Commun. Lett.*, vol. 14, pp 390-392, May 2010.
[13] A. Antoniou and W.-S. Lu, *Practical Optimization: Algorithms and Engineering Applications*. Spring Street, NY: Springer Science+Business Media, LCC, 2007.