Secure Beamforming and Artificial Noise Design for Simultaneous Wireless Information and Power Transfer in Interference Networks

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***Abstract*—We study a secure communication of a two-user interference network. In this network, two transmitters send information and artificial noise simultaneously to two users and energy receivers (ERs), and ERs are likely to perform as eavesdroppers. We propose a joint beamforming and artificial noise design to maximize the total energy harvested by ERs subject to the secrecy sum rate requirement and power constraints. The proposed design constitutes an optimization problem, which is non-convex yet can be further transformed into a two-stage problem. In the first stage, by introducing an auxiliary variable, we can reformulate the non-convex as a second-order cone program (SOCP) problem, and the constrained concave convex procedure based algorithm is proposed to make this SOCP problem tractable. In the second stage, the auxiliary variable is obtained by the one-dimensional line search. Numerical results demonstrate the effectiveness of the proposed algorithm.**

I. Introduction

The growing energy demand of wireless communication system has drawn attention of both academia and industry. Energy harvesting (EH) has been considered as a promising technique to expand the lifetime of network by providing safe and green energy from the environment. In EH, ambient radio-frequency (RF) can be the energy source for energy receivers (ERs). RF signal can carry information and energy at the same time, as a consequence, the scheme named simultaneous wireless information and power transfer (SWIPT) comes into being [1]–[5]. It is also worth noting that ERs are not only able to collect energy, but also intercept the messages sent to other intended users, which brings great challenges to the security of the SWIPT systems.

The wireless research community's interest in physical-layer security (PLS) has received much attention because of its independence of the interception ability of eavesdroppers [6]. From the perspective of PLS, how to guarantee the secrecy communication of SWIPT system is a hot topic in recent years [7]–[10]. In [7], a relaying technique is proposed to enhance the PLS in SWIPT, but the proposed scheme and analyses are not effective in the case of small number of the antennas. In [8], for the three-node single-input single-output wiretap fading channel, an artificial noise (AN) aided transmission scheme is proposed to facilitate the secrecy information transmission to information receivers subject to the EH requirement of ERs, whereas this scheme is only applied in single-antenna nodes. The AN and beamforming are applied to guarantee a secure communication for the multiple-input single-output (MISO) and multiple-input multiple-output system in [9] and [10] respectively. To the best of our knowledge, the topics on the interference network with ERs trying to intercept the transmitters have not been studied, and due to the existence of the interference, the previous work cannot be extends into the interference network straightforwardly. This motivates us to tackle this challenging problem.

In this paper, we study the secrecy transmission of a two-user MISO interference network with some ERs. It is noted that the ERs are supposed to only scavenge energy, but likely to decode the information sent to two intended information receivers from RF signals. We propose a joint beamforming and artificial noise (BF-AN) design scheme aimed to maximize the total energy harvested by the ERs subject to the individual power constraints of the transmitters and the secrecy sum rate requirement. In this model, both the information beams and artificial noise are the energy sources for the ERs. It can be observed that the joint design of the beamforming and AN is difficult, because it turns out to be a non-convex problem. The main contribution of this paper is to make this non-convex problem more tractable by decomposing it into a two-stage problem equivalently, and propose an effective algorithm to solve it. Further more, in the first stage, we introduce an auxiliary variable, then we can solve the non-convex optimization problem by reformulating it as a second-order cone program (SOCP) problem, and we propose a constrained concave convex procedure (CCCP) based iterative algorithm to solve the SOCP problem. The second stage is to find the auxiliary variable by the one-dimensional line search.

Notations: Bold upper and lower case letters denote matrices and vectors, respectively. $(\cdot)^H$ denotes the conjugate transpose. $\mathbb{E}\{\cdot\}$ represents expectation. $\mathbb{C}^{N\times M}$ denotes an $N\times M$ complex matrix. $|\cdot|$ represents the mode for a complex number. $[x]^+$ denotes $\max(0,x)$. $\mathrm{Tr}(\cdot)$ is the trace operator. $\mathcal{CN}(\mu,\sigma^2)$ denotes the circularly symmetric complex Gaussian distribution with mean μ and variance σ^2.

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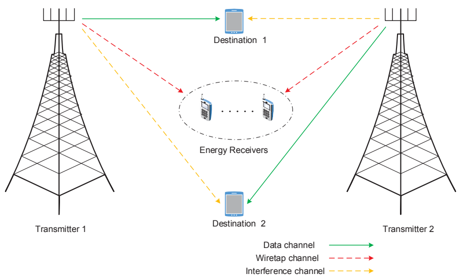

Fig. 1. Two-user interference network with energy receivers

II. System Model And Problem Formulation

We consider a MISO interference network for SWIPT which consists of two transmitters denoted by T_1 and T_2, K ERs denoted by $\mathcal{K}_{\mathrm{ER}} = \{\mathrm{ER}_1, \ldots, \mathrm{ER}_K\}$ and two information receivers denoted by D_1 and D_2 as shown Fig .1. T_1 and T_2 are respectively equipped with N_1 and N_2 antennas, while two information receivers and ERs are equipped with one antenna. These ERs are supposed to harvest energy, but they are likely to act as non-colluding eavesdroppers, decoding the massages sent to D_1 and D_2 by T_1 and T_2.

T_i, $i \in \{1, 2\}$, sends confidential message to D_i and AN for security, i.e.,

$$\mathbf{x}_i = \mathbf{w}_i s_i + \mathbf{z}_i, \quad (1)$$

where $\mathbf{w}_i \in \mathbb{C}^{N_i \times 1}$ is the beamforming vector and $\mathbf{z}_i \sim \mathcal{CN}(0, \mathbf{Z}_i)$ is the AN vector sent by T_i, and $\mathbf{Z}_i$ represents the covariance matrix of $\mathbf{z}_i$. Furthermore, s_i denotes the intended signal to D_i, $i \in \{1, 2\}$, which is an independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian (CSCG) random variable denoted by $s_i \sim \mathcal{CN}(0, 1)$.

The received signals at the j-th intended user D_j and k-th energy harvester ER_k, are given by

$$y_j = \sum_{i=1}^{2} \mathbf{h}_{ij}^H \mathbf{x}_i + n_j, \text{ and } y_{\mathrm{ER}_k} = \sum_{i=1}^{2} \mathbf{g}_{ik}^H \mathbf{x}_i + n_{\mathrm{ER}_K}, \quad (2)$$

respectively, where $\mathbf{h}_{ij} \in \mathbb{C}^{N_i \times 1}$, $i, j \in \{1, 2\}$ and $\mathbf{g}_{ik} \in \mathbb{C}^{N_i \times 1}$, $i \in \{1, 2\}$ are the baseband complex channel from T_i to D_j and ER_k, respectively, and we assume that the channel fading is frequency non-selective Rayleigh block fading, which means the fading coefficients $\mathbf{h}_{ij}$ and $\mathbf{g}_{ik}$ remain constant during one time slot, but change independently from one time slot to another. $n_j \sim \mathcal{CN}\left(0, \sigma_{\mathrm{j}}^2\right)$ and $n_{\mathrm{ER}_k} \sim \mathcal{CN}\left(0, \sigma_{\mathrm{ER}_k}^2\right)$ represent the additive white Gaussian noise (AWGN) at D_j and EH_k, respectively. Without loss of generality, it is assumed that $\sigma_j^2 = \sigma_{\mathrm{ER}_k}^2 = 1$. Since ERs are designed to scavenge energy, the channel state information (CSI) of ERs should be fed to the transmitters for the sake of designing transmit beamforming to satisfy their individual energy requirements. Therefore, it is reasonable to assume that the global CSI is collected in a central processing unit in which the beamforming vectors for both transmitters are jointly designed.

In this model, the energy comes from two parts: information beams and AN, i.e., $\mathbf{w}_i$ and $\mathbf{z}_i$. Assuming unit slot duration, the energy harvested by all ERs in each slot can be expressed as [3]

$$E = \sum_{i=1}^{2} \sum_{k=1}^{K} \zeta \left(\left| \mathbf{g}_{ik}^H \mathbf{w}_i \right|^2 + \left| \mathbf{g}_{ik}^H \mathbf{z}_i \right|^2 \right), k = 1, \ldots, K, \quad (3)$$

where $0 \leq \zeta \leq 1$ denotes the energy harvesting efficiency.

We assume that user D_j perceives the signal from the other transmitter, and AN from T_i, $i \in \{1, 2\}$ as noise. The signal-to-interference-plus-noise ratio (SINR) at each user can be expressed as

$$\gamma_i = \frac{\left| \mathbf{h}_{ii}^H \mathbf{w}_i \right|^2}{\left| \mathbf{h}_{ii}^H \mathbf{z}_i \right|^2 + \left| \mathbf{h}_{\bar{i}i}^H \mathbf{z}_{\bar{i}} \right|^2 + \left| \mathbf{h}_{\bar{i}i}^H \mathbf{w}_{\bar{i}} \right|^2 + \sigma_i^2}, \quad (4)$$

where $\bar{1} = 2, \bar{2} = 1$. The sum of the channel capacity for transmitters to the ER_k can be expressed as the maximum sum-rate of a two-user multiple-access channel, given by [11]

$$\begin{aligned} C_{\mathrm{ER}_k} &= I\left(y_{\mathrm{ER}_k}; s_1, s_2\right) \\ &= \log_2 \left(1 + \frac{\left| \mathbf{g}_{1k}^H \mathbf{w}_1 \right|^2 + \left| \mathbf{g}_{2k}^H \mathbf{w}_2 \right|^2}{\left| \mathbf{g}_{1k}^H \mathbf{z}_1 \right|^2 + \left| \mathbf{g}_{2k}^H \mathbf{z}_2 \right|^2 + \sigma_{\mathrm{ER}_k}^2} \right), \forall k. \quad (5) \end{aligned}$$

Let C_i denote the capacity for T_i to the its intended user D_i. According to [12], the achievable secrecy sum rate of the two transmitters is thus expressed as

$$\begin{aligned} r_0 &= \min_{1 \leq k \leq K} \left[C_1 + C_2 - C_{\mathrm{ER}_k} \right]^+ \quad (6) \\ &= \min_{1 \leq k \leq K} \left[\log_2 \left(1 + \gamma_1 + \gamma_2 + \gamma_1 \gamma_2\right) - \log_2 \left(1 + \gamma_{\mathrm{ER}_k}\right) \right]^+, \end{aligned}$$

where

$$\gamma_{\mathrm{ER}_k} = \frac{\left| \mathbf{g}_{1k}^H \mathbf{w}_1 \right|^2 + \left| \mathbf{g}_{2k}^H \mathbf{w}_2 \right|^2}{\left| \mathbf{g}_{1k}^H \mathbf{z}_1 \right|^2 + \left| \mathbf{g}_{2k}^H \mathbf{z}_2 \right|^2 + \sigma_{\mathrm{ER}_k}^2}.$$

Our goal is to find the maximum total energy harvested by all ERs subject to the individual transmission power constraint and the secrecy sum rate requirement. The problem can be formulated as

$$\max_{\substack{\mathbf{w}_1, \mathbf{w}_2, \\ \mathbf{Z}_1, \mathbf{Z}_2}} \sum_{i=1}^{2} \sum_{k=1}^{K} \zeta \left(\left| \mathbf{g}_{ik}^H \mathbf{w}_i \right|^2 + \left| \mathbf{g}_{ik}^H \mathbf{z}_i \right|^2 \right) \quad (7a)$$

$$\text{s.t. } r_0 \geq \bar{r}_0, \quad (7b)$$

$$\left\| \mathbf{w}_i \right\|^2 + \mathrm{Tr}\left(\mathbf{Z}_i\right) \leq P_i, i \in \{1, 2\}, \quad (7c)$$

where $\bar{r}_0$ is the threshold of the secrecy sum rate which we want to achieve, and P_i is power budget of transmitter T_i.

III. THE PROPOSED JOINT BF-AN DESIGN

It can be seen that problem (7) is a non-convex optimization problem, so it is difficult to solve. In this section, a CCCP based algorithm will be proposed to solve the problem (7). First, to deal with (7), we have the following lemma.

Lemma 1. *Problem (7) has the same optimal solution and value as those of the following problem,*

$$\max_{\substack{\mathbf{w}_1,\mathbf{w}_2,\gamma_0,\\ \mathbf{Z}_1,\mathbf{Z}_2}} \quad \sum_{i=1}^{2}\sum_{k=1}^{K}\zeta\left(\left|\mathbf{g}_{ik}^H\mathbf{w}_k\right|^2+\left|\mathbf{g}_{ik}^H\mathbf{z}_k\right|^2\right) \tag{8a}$$

$$\text{s.t.} \quad \gamma_1+\gamma_2+\gamma_1\gamma_2 \geq \gamma_0, \tag{8b}$$

$$\gamma_{\mathrm{ER}_k} \leq \frac{1+\gamma_0}{2^{\bar{r}_0}}-1,\ \forall k \tag{8c}$$

$$\|\mathbf{w}_i\|^2+\mathrm{Tr}\left(\mathbf{Z}_i\right) \leq P_i,\ i\in\{1,2\}. \tag{8d}$$

Proof: please refer to Appendix. ■

Problem (8) can be converted into a two-stage optimization problem. Let the function $f\left(\gamma_0\right)$ denote the optimal value of problem (8) with the auxiliary variable γ_0. The first stage is to find the optimal value $f\left(\gamma_0\right)$ for a given $\gamma_0>0$. In the next stage, we need to find the optimal γ_0^* of problem (8) to obtain the maximum $f\left(\gamma_0^*\right)$, and in this stage, one-dimensional line search, e.g., Golden Section Search, can be applied. Then, the optimal value $f\left(\gamma_0^*\right)$ can be obtained. To this end, let us go back to the first stage where the main challenge is the fact that problem (8) is not an convex problem with any given γ_0. In the rest of this section, we aim to solve the first stage.

A. Transformation of (8b)

Obviously, (8b) can be expressed as

$$\gamma_1 \geq \frac{\gamma_0+1}{\gamma_2+1}-1. \tag{9}$$

To make it more tractable, we firstly introduce two slack variables p and q, and then (9) can be equivalently transformed into

$$p \geq \frac{\gamma_0+1}{q}-1,\ \gamma_1 \geq p,\ \gamma_2 \geq q-1. \tag{10}$$

Then, it is noted that the second and third item of (10) are non-convex. we can introduce two slack variables v_1 and v_2, then the second item can be equivalently transformed into

$$\frac{\mathbf{w}_1^H\mathbf{H}_{11}\mathbf{w}_1}{v_1} \geq p, \tag{11a}$$

$$\left|\mathbf{h}_{11}^H\mathbf{z}_1\right|^2+\left|\mathbf{h}_{21}^H\mathbf{z}_2\right|^2+\left|\mathbf{h}_{21}^H\mathbf{w}_2\right|^2+\sigma_1^2 \leq v_1. \tag{11b}$$

Based on the fact that $a^2\leq bc$ is equivalent to the second-order cone (SOC) form $\|[2a,b-c]\|\leq b+c$, where $b\geq 0$, $c\geq 0$, (11b) can be expressed

$$\left\|\left[2\mathbf{h}_{11}^H\mathbf{z}_1,\ 2\mathbf{h}_{21}^H\mathbf{z}_2,\ 2\mathbf{h}_{21}^H\mathbf{w}_2,\ 2\sigma_1,\ v_1-1\right]\right\| \leq v_1+1, \tag{12}$$

and SOC form of the first item of (10) can be expressed as

$$\left\|\left[2\sqrt{\gamma_0+1},p+1-q\right]\right\| \leq p+1+q. \tag{13}$$

Similarly, the third item of (10) can be expressed as

$$\frac{\mathbf{w}_2^H\mathbf{H}_{22}\mathbf{w}_2}{v_2} \geq q-1, \tag{14a}$$

$$\left\|\left[2\mathbf{h}_{12}^H\mathbf{z}_1,\ 2\mathbf{h}_{22}^H\mathbf{z}_2,\ 2\mathbf{h}_{12}^H\mathbf{w}_1,\ 2\sigma_2,\ v_2-1\right]\right\| \leq v_2+1, \tag{14b}$$

respectively, where $\mathbf{H}_{ii}=\mathbf{h}_i\mathbf{h}_i^H,\ i\in\{1,2\}$. According to [13], the function $\zeta\left(\mathbf{w},v\right)=\frac{\mathbf{w}^H\mathbf{H}\mathbf{w}}{v}$ is convex in $\mathbf{w}$ and v, where $\mathbf{H}\succeq 0$, $v\geq 0$. Then, considering that when a constraint is that a convex function is smaller than or equal to a concave function, the constraint is a convex constraint [13], we know the constraints (11a) and (14a) are not convex constraints. To deal with this problem, (11a) and (14a) can be approximated by the first order Taylor approximation: the first order Taylor expansion of $\zeta\left(\mathbf{w},v\right)=\frac{\mathbf{w}^H\mathbf{H}\mathbf{w}}{v}$ around the point $(\tilde{\mathbf{w}},\tilde{v})$ can be written as [14]

$$\zeta\left(\mathbf{w},v,\tilde{\mathbf{w}},\tilde{v}\right)=\frac{2\mathrm{Re}\left\{\tilde{\mathbf{w}}^H\mathbf{H}\mathbf{w}\right\}}{\tilde{v}}-\frac{\tilde{\mathbf{w}}^H\mathbf{H}\tilde{\mathbf{w}}}{\tilde{v}^2}v. \tag{15}$$

Note that (15) is a linear function about $(\mathbf{w},v)$. By applying the idea of CCCP, (11a) and (14a) can be transformed into

$$\mathrm{Re}\{\mathbf{m}_1\mathbf{w}_1\}-n_1v_1 \geq p, \tag{16a}$$

$$\mathrm{Re}\{\mathbf{m}_2\mathbf{w}_2\}-n_2v_2 \geq q-1, \tag{16b}$$

respectively, where

$$\mathbf{m}_i=\frac{2}{\tilde{v}_i^{(n)}}\left(\tilde{\mathbf{w}}_i^{(n)}\right)^H\mathbf{H}_{ii},n_i=\frac{1}{\left(\tilde{v}_i^{(n)}\right)^2}\left(\tilde{\mathbf{w}}_i^{(n)}\right)^H\mathbf{H}_{ii}\tilde{\mathbf{w}}_i^{(\mathrm{n})},$$

and $\tilde{\mathbf{w}}_i^{(n)}$ and $\tilde{v}_i^{(n)}$ denote the solution to problem (8) about $\mathbf{w}_i$ and v_i at the nth iteration. Now, (16) are typical convex constraints.

B. Transformation of (8c)

It is obvious that (8c) is also not a convex constraint. Note that when $\bar{r}_0$ and γ_0 are given, the right-hand side of (8c) is a constant. Then it can be expressed as

$$\left|\mathbf{g}_{1k}^H\mathbf{w}_1\right|^2+\left|\mathbf{g}_{2k}^H\mathbf{w}_2\right|^2 \leq l\left[\mathrm{Tr}\left(\sum_{i=1}^{2}\mathbf{G}_{ik}\mathbf{Z}_i\right)+\sigma_{\mathrm{ER}_k}^2\right],\ \forall k \tag{17}$$

where $l=\left(1+\gamma_0\right)/2^{\bar{r}_0}-1$, and $\mathbf{G}_{ik}=\mathbf{g}_{ik}\mathbf{g}_{ik}^H,\ i\in\{1,2\}$. Then, the SOC form of (17) can be expressed as

$$\left\|\left[2\mathbf{g}_{1k}^H\mathbf{w}_1,2\mathbf{g}_{2k}^H\mathbf{w}_2,d-1\right]\right\| \leq d+1,\ \forall k, \tag{18}$$

where $d=l\left[\mathrm{Tr}\left(\sum_{i=1}^{2}\mathbf{G}_{ik}\mathbf{Z}_i\right)+\sigma_{\mathrm{ER}_k}^2\right]$. According to [13], (18) is a convex constraint.

Similar as (18), the power constraints (8d) can be equally expressed as

$$\|[2\mathbf{w}_i,P_i-\mathrm{Tr}\left(\mathbf{Z}_i\right)-1]\| \leq P_i-\mathrm{Tr}\left(\mathbf{Z}_i\right)+1, \tag{19}$$

C. Transformation of (8a)

Up till now, all the constrains of problem (8) are handled. But notice that the objective function of problem (8) is non-concave. The objective function can be written as

$$\max_{\mathbf{w}_i,\mathbf{Z}_i,i\in\{1,2\}} \sum_{i=1}^{2}\sum_{k=1}^{K}\zeta\left(\mathbf{w}_i^H\mathbf{G}_{ik}\mathbf{w}_i+\mathrm{Tr}\left(\mathbf{G}_{ik}\mathbf{Z}_i\right)\right). \tag{20}$$

It is obvious that we cannot maximize a non-concave function by the convex optimization theory. Thus, to handle

Algorithm 1 CCCP based algorithm for solving (24)

1. Initialization: Set u, γ_0, ϵ, $n = 0$, $\left(\tilde{\mathbf{w}}_i^{(n)}, \tilde{v}_i^{(n)}\right) = \left(\mathbf{w}_i^0, v_i^0\right)$ which are feasible to (24).
2. While 1

   Solve the SOCP (24) with $\left(\tilde{w}_i^{(n)}, \tilde{v}_i^{(n)}\right)$, and obtain the optimal value u^*, and the optimal solutions (w_i^*, v_i^*) in the $(n+1)$th iteration.

   If $|u^* - u| \le \epsilon$

   stop;

   End

   Update
$$u = u^*,$$
$$\left(\tilde{w}_i^{(n+1)}, \tilde{v}_i^{(n+1)}\right) = (w_i^*, v_i^*),$$
$$n = n + 1.$$

   End
3. Search for γ_0 by one-dimensional line search.
4. Repeat step 2 and 3, until the maximum $f(\gamma_0^*)$ is found.

this problem, we can introduce a slack variable u. Then, the problem is

$$\max_{\substack{\mathbf{w}_i, \mathbf{Z}_i, v_i, p, q, u, \\ i \in \{1,2\}}} \quad u \tag{21a}$$

$$\text{s.t. } u \le \sum_{i=1}^{2}\sum_{k=1}^{K} \zeta\left(\mathbf{w}_i^H \mathbf{G}_{ik} \mathbf{w}_i + \mathrm{Tr}\left(\mathbf{G}_{ik}\mathbf{Z}_i\right)\right), \forall k \tag{21b}$$

$$v_1, v_2, p, q, u \ge 0, \tag{21c}$$

$$(12), (13), (14b), (16), (18), (19). \tag{21d}$$

However, it is obvious that (21b) is not a convex constraint, since the functions of the type such as $\mathbf{w}^H \mathbf{H} \mathbf{w}$ are convex about $\mathbf{w}$. To deal with it, we approximate it by its first order Taylor approximation. According to [14], the first order Taylor expansion of $\zeta(\mathbf{w}) = \mathbf{w}^H \mathbf{H} \mathbf{w}$ around the point $\tilde{\mathbf{w}}$ is

$$\zeta(\mathbf{w}, \tilde{\mathbf{w}}) = 2\mathrm{Re}\left\{\tilde{\mathbf{w}}^H \mathbf{H} \mathbf{w}\right\} - \tilde{\mathbf{w}}^H \mathbf{H} \tilde{\mathbf{w}}. \tag{22}$$

It can be seen that (22) is a linear function with $\mathbf{w}$. Thus, based on the idea of CCCP, (21b) can be approximated as

$$u \le \sum_{i=1}^{2}\sum_{k=1}^{K} \zeta\left[\left(2\mathrm{Re}\left\{\mathbf{s}_{ik}\mathbf{w}_i\right\} - n_{ik}\right) + \mathrm{Tr}\left(\mathbf{G}_{ik}\mathbf{Z}_i\right)\right], \forall k \tag{23}$$

where $\mathbf{s}_{ik} = \left(\tilde{\mathbf{w}}_i^{(n)}\right)^H \mathbf{G}_{ik}$, $n_{ik} = \left(\tilde{\mathbf{w}}_i^{(n)}\right)^H \mathbf{G}_{ik} \tilde{\mathbf{w}}_i^{(n)}$, and $\tilde{\mathbf{w}}_i^{(n)}$ and $\tilde{v}_i^{(n)}$ denote the solution to problem (21) about $\mathbf{w}_i$ and v_i at the nth iteration. Now, (23) is a typical convex constraint. Finally, the original problem (8) can be recast as

$$\max_{\substack{\mathbf{w}_i, \mathbf{Z}_i, v_i, p, q, u, \\ i \in \{1,2\}}} \quad u \tag{24a}$$

$$\text{s.t. } (21c), (21d), (23). \tag{24b}$$

It is noted that problem (24) is an SOCP problem, which can be solved by numerical solvers such as SeDuMi [15]. The proposed iterative algorithm is summarized in Algorithm 1.

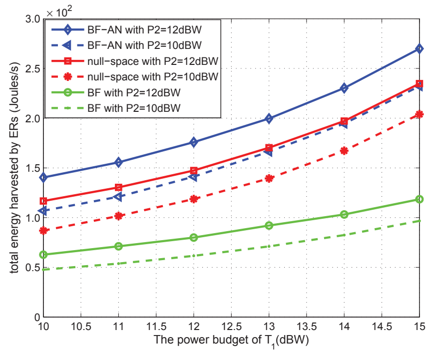

Fig. 2. The total energy harvested by ERs versus P_1 for $\bar{r}_0 = 3.5$bps/Hz.

Remark 1. The algorithm converges to a local optimal solution after a few iterations. For each given γ_0, the optimal solutions of problem (24), i.e., $(\mathbf{w}_i^*, \mathbf{Z}_i^*, v_i^*, p^*, q^*, u^*)$, are obtained by solving (24) for a given $(\tilde{\mathbf{w}}_i, \tilde{v}_i)$. For each iteration, $(\tilde{\mathbf{w}}_i, \tilde{v}_i)$ is updated from the optimal solutions of the last iteration. Therefore, $(\tilde{\mathbf{w}}_i, \tilde{v}_i)$ is always feasible for the next iteration, and the optimal value u^* becomes larger or equal to that of last iteration. Hence, the total energy harvested will be monotonically increasing or non-decreasing at each iteration. There exists an upper bound because of the power constraint, which means Algorithm 1 is convergent as showed in Fig. 4.

Up to now, with a given γ_0, we can deal with the first stage of problem (8). The second stage is to find the optimal γ_0^* by one-dimensional line search until the maximum $f(\gamma_0^*)$ is obtained.

IV. Simulations

In this section, the convergence behaviors of the design is examined and the total energy harvested by ER_k is also evaluated. In our simulation, we assume that the energy harvesting efficiency $\zeta = 1$, and all channels are randomly generated following an i.i.d CSCG distribution with zero mean and unit variance. We use the numerical solvers, i.e., SeDuMi [15], to solve the optimization problems.

We propose a null-space beamforming design to guarantee the secure communication and compare its effectiveness with BF-AN design. In the null-space beamforming design, the information for intended users are not leaked to the potential eavesdroppers, i.e., $\mathbf{g}_{ik}^H \mathbf{w}_k = 0$, which also means ER_k can only harvest energy from AN. The same algorithm can be applied in this situation, but there is no need to search for γ_0 in the algorithm. Fig. 2 shows that the total energy harvested by all ERs of different schemes versus the power budget of T_1 for different P_2 with $N_1 = N_2 = 4$, $\bar{r}_0 = 3.5$bps/Hz and $K = 2$. It can be seen that the total energy increase monotonically with P_1. We can also observe that the joint BF-AN design outperforms the null-space one, which surpasses BF design only. The difference between BF-AN design and BF design only is more significant than that between BF-AN design and null-space design. Therefore, we can conclude that null-space design is totally secure, but compared with BF-AN design,

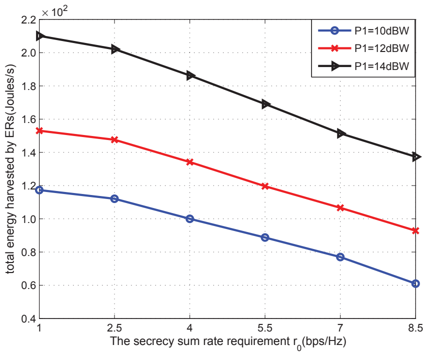

Fig. 3. The total energy harvested by ERs versus secrecy sum rate requirement

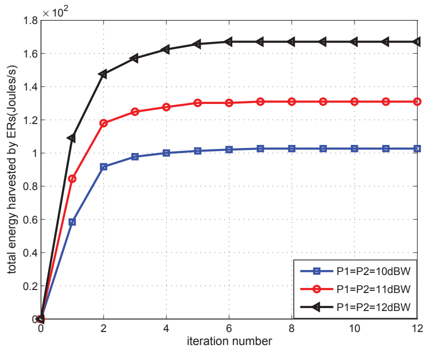

Fig. 4. Convergence property according to different power budget

the amount of energy harvested is less, and AN is the major energy source for ERs, meanwhile, the energy from BF also cannot be overlooked.

In Fig. 3, we show that the total energy versus the threshold $\bar{r}_0$ for different P_1, with $N_1 = N_2 = 4$ and $K = 2$ in BF-AN design. As we can see, as the $\bar{r}_0$ increases, the total energy harvested will decrease monotonically, which means there is a trade-off between the energy harvested and secrecy sum rate.

Fig. 4 represents the convergence behaviors of Algorithm 1 in solving problem (8) for different power budget with $N_1 = N_2 = 4$ and $K = 2$, $\bar{r}_0 = 3.5$bps/Hz. It shows that the algorithm converges in a few steps and the total energy increases monotonically.

V. Conclusions

We study the joint BF-AN design which can maximize the total energy subject to the individual power at each transmitter and the secrecy sum rate requirement in the two-user MISO interference network with some energy harvesters which may act as eavesdroppers to decode the messages sent to intended users. We decompose the non-convex optimization problem into a two-stage problem. The first stage is to solve the non-convex problem by an iterative algorithm, and the next stage is a one-dimensional line search problem. From the simulation, it can be seen that our algorithm is effective in solving this optimization problem.

Appendix

It is easy to be seen that any optimal solution to problem (7) , denoted by $\mathbf{w}_i^*$ and $\mathbf{Z}_i^*$, $i \in \{1, 2\}$, is also optimal for problem (8) with

$$\gamma_0 = \frac{\left|\mathbf{h}_{11}^H \mathbf{w}_1^*\right|^2}{\left|\mathbf{h}_{11}^H \mathbf{z}_1^*\right|^2 + \left|\mathbf{h}_{21}^H \mathbf{z}_2^*\right|^2 + \left|\mathbf{h}_{21}^H \mathbf{w}_2^*\right|^2 + \sigma_1^2} + \frac{\left|\mathbf{h}_{22}^H \mathbf{w}_2^*\right|^2}{\left|\mathbf{h}_{12}^H \mathbf{z}_1^*\right|^2 + \left|\mathbf{h}_{22}^H \mathbf{z}_2^*\right|^2 + \left|\mathbf{h}_{12}^H \mathbf{w}_1^*\right|^2 + \sigma_2^2}$$
$$+ \frac{\left|\mathbf{h}_{11}^H \mathbf{w}_1^*\right|^2}{\left|\mathbf{h}_{11}^H \mathbf{z}_1^*\right|^2 + \left|\mathbf{h}_{21}^H \mathbf{z}_2^*\right|^2 + \left|\mathbf{h}_{21}^H \mathbf{w}_2^*\right|^2 + \sigma_1^2} \cdot \frac{\left|\mathbf{h}_{22}^H \mathbf{w}_2^*\right|^2}{\left|\mathbf{h}_{12}^H \mathbf{z}_1^*\right|^2 + \left|\mathbf{h}_{22}^H \mathbf{z}_2^*\right|^2 + \left|\mathbf{h}_{12}^H \mathbf{w}_1^*\right|^2 + \sigma_2^2}.$$

Thus, we have $\max\limits_{\gamma_0 > 0} f(\gamma_0) \geq t^*$, and $f(\gamma_0)$ denotes the optimal value of problem (8) with a given $\gamma_0 > 0$ and t^* is the optimal value of problem (7). Then, it can be seen that the optimal solution $\mathbf{w}_i^*$ and $\mathbf{Z}_i^*$ to problem (8) is also feasible for problem (7), which means $t^* \geq \max\limits_{\gamma_0 > 0} f(\gamma_0)$. Hence, we have $\max\limits_{\gamma_0 > 0} f(\gamma_0) = t^*$. The bound about γ_0 can be written as

$$0 \leq \gamma_0 < \mathrm{Tr}(\mathbf{H}_{11}) P_1 + \mathrm{Tr}(\mathbf{H}_{22}) P_2 + \mathrm{Tr}(\mathbf{H}_{11}) P_1 \mathrm{Tr}(\mathbf{H}_{22}) P_2. \quad (25)$$

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