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Secrecy Rate Optimization for Cooperative Cognitive Radio Networks Aided by a Wireless Energy Harvesting Jammer

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ABSTRACT In this paper, a novel wireless energy harvesting cooperative jammer (EH-CJ)-aided transmission scheme, which can enhance the security for cooperative cognitive radio networks (CCRNs), is proposed. The EH-CJ first harvests energy from ambient radio frequency (RF) signals transmitted from the primary transmitter (PT). This energy is then used to transmit jamming noise (JN), so that the performance of eavesdroppers' receptions is degraded, and also to deliver additional power to the secondary energy receiver (ER). In this way, the proposed scheme can enhance the security and extend the lifetime for CCRNs. For this system, we formulate an optimization problem for maximizing the secrecy rate of the secondary system under transmit power constraints at the secondary transmitter as well as the EH-CJ, minimum harvested energy at the secondary ER and information rate at the primary receiver (PR). Since this optimization problem is not convex, we propose a two-stage optimization algorithm based upon the Charnes–Cooper transformation and rank-one relaxation to solve it. Computer simulation results have demonstrated that the proposed EH-CJ-aided scheme achieves better secrecy rate performance, as compared to an isotropic JN scheme as well as compared to an equivalent scheme which does not use the aid of EH-CJ.

INDEX TERMS Cognitive radio, physical layer security, cooperative jammer, secure beamforming, energy harvesting.

I. INTRODUCTION

Due to the dramatical increase of data traffic, cognitive radio has emerged as a promising technology of increasing the spectrum efficiency in wireless networks [1]. In recent years, a new paradigm named cooperative cognitive radio networks (CCRNs) has been proposed to improve spectral efficiency of cognitive radio networks [2]–[5]. With this cooperative transmission strategy, the secondary transmitter (ST) can aid the primary transmitter (PT) to relay information to the primary receiver (PR), and in return the ST can utilize the primary spectrum to transmit its own information.

However, because the broadcasting nature of wireless communication makes the information vulnerable to eavesdropping, the physical layer security (PLS) has been long recognized as an important condition for the proper operation of CCRNs [6]. The theoretical basis for the PLS was first proposed by Wyner [7] in his seminal work, in which he has introduced the wiretap channel and defined secrecy capacity. In recent years, the emerging requirement for preventing eavesdropping has led to the publication of several PLS techniques which have been proposed to enhance the security of various wireless communication systems, e.g. see [8]–[13]. More specifically, in order to take advantage of the benefits of the spatial degree of freedom provided by the multiple transmit antennas, transmit beamforming has been used to improve the secrecy performance of multiple-

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input single-output (MISO) systems [8]. In another approach, the concept of artificial noise (AN), first introduced by Negi and Goel [9], was used to enhance PLS by embedding noise in the transmitted signal. For example, in [10], an AN aided scheme was proposed to maximize the achievable secrecy rate of both primary and secondary links for the overlay CCRNs. In [11], a joint design of transmit and AN beamformings was proposed aiming at minimizing the transmit power at the ST while guaranteeing the security for both PR and secondary receiver (SR). In [12], the cooperative jammer (CJ) approach was employed to generate jamming signal to degrade the eavesdroppers' reception. In [13], both relay-jammer and collaborative beamforming schemes were used for improving the security of the primary system.

It is noted that, since these secure transmission schemes require only a fraction of the transmit power, the transmit node is energy-constrained, and thus energy scarcity becomes the bottleneck for enhancing the secrecy performance. This observation has led to the concept of wireless power transfer (WPT), which, in conjunction with simultaneous data transmission, is widely known as simultaneous wireless information and power transfer (SWIPT) [14]–[17]. WPT is a very promising energy harvesting (EH) technique for prolonging the lifetime of energy-constrained systems, whereby the wireless communication devices can harvest energy from radio frequency (RF) signals. Focusing now on the security aspects of the networks employing WPT, it is noted that, although recently several papers have been published on this topic (see e.g. [18]–[23]), most of them deal, one way or another, with conventional and/or cognitive radio networks. As far as the problem of secure communications for CCNRs employing WPT is concerned, to the best of our knowledge, there exit only few publications, i.e. [22] and [23]. More specifically, Wu and Chen [22] have proposed a joint robust beamforming and power splitting scheme to minimize the transmit power at the ST for the CCRNs. However, in their design they have only considered the harvested energy constraints at the PR and SR, without considering of how to best use the harvested power. On the other hand, Jiang *et al.* [23] have investigated the joint design of secure beamforming and power splitting at the EH ST to maximize the secondary system rate subject to the secrecy requirement of the primary system. However, they assumed that only single-antenna eavesdroppers were present in their considered networks. It is also noted that the secrecy performance of their design would become worse when multiple multi-antenna eavesdroppers existed, as this would cause more secrecy degradation.

In this paper, we follow another approach which takes advantage of the jammer signal to enhance the security aspects of CCRNs. In particular, we propose a novel wireless energy harvesting cooperative jammer (EH-CJ)-aided scheme to guarantee secure communication for CCRNs in the presence of multiple multi-antenna eavesdroppers. The EH-CJ is employed to supply more energy to the secondary energy receiver (ER), and also to degrade the performance of potential malicious eavedroppers' receptions. In order to do so, we consider not only the harvested energy constraint at the ER, but also how to take advantage of the harvested energy at the EH-CJ to generate jamming noise[1] (JN), to confound the eavesdroppers. Aiming at maximizing the secrecy rate of secondary system, we formulate the achievable secrecy rate maximization problem subject to power constraints at the secondary system and information rate constraint at the PR. Specifically, we maximize the achievable secrecy rate by jointly designing the retransmit beamforming matrix and transmit beamforming vector at the ST and the covariance matrix at the EH-CJ. To solve this non-convex problem, we propose a two-stage optimization algorithm using the Charnes-Cooper transformation and semidefinite relaxation (SDR) techniques. For comparison purposes, and in order to show the superiority of our novel scheme, we also obtain the performance of the isotropic JN scheme and the scheme without the aid of EH-CJ.

The rest of paper is organized as follows: In Section II, we describe with details the system model. In Section III, we present both the EH-CJ-aided and isotropic JN schemes and also analyze the optimization problem which maximizes the achievable secrecy rate of the secondary system. Various performance evaluation results obtained by means of Monte-Carlo computer simulations are presented in Section IV. The conclusions of the paper can be found in Section V.

Notations: $|\cdot|$ denotes the absolute value of a complex scalar. $(\cdot)^H$, $\mathrm{Tr}(\cdot)$, $\det(\cdot)$, $\|\cdot\|$, $rank(\cdot)$, $(\cdot)^{-1}$ and $\mathrm{BD}(\cdot)$ denote the conjugate transpose, trace, determinant, Frobenius norm, rank, inverse and block diagonalization of a matrix, respectively. $vec(\cdot)$ means column-by-column matrix vectorization. $\mathbf{1}$ indicates a vector (or matrix) where all elements are one. $\mathbf{I}$ denotes the identity matrix. $\otimes$ and $\odot$ denote the Kronecker product and Hadamard product, respectively. $\mathbb{E}[\cdot]$ means the statistical expectation for random variables. $[a]^+$ means $\max\{a, 0\}$. $\mathbf{A} \succeq 0$ indicates that $\mathbf{A}$ is a positive semidefinite matrix. $\mathbb{C}^N$ denotes the space of $N \times 1$ matrices with complex entries. $\mathbf{x} \sim \mathcal{CN}(\mathbf{m}, \mathbf{V})$ means that vector $\mathbf{x}$ is complex Gaussian distributed with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{V}$.

II. SYSTEM MODEL

We consider secure communication for CCRNs in the presence of multiple multi-antenna eavesdroppers, as shown through the block diagram of Fig. 1. The primary system consists of a PT and a PR, whereas the secondary system consists of an ST, an EH-CJ, one legitimate information receiver (IR), one ER and K malicious eavesdroppers, each of which is referred to as Eve-k ($k = 1, 2, \ldots, K$) and collectively as "Eves". It is assumed that the ST and the EH-CJ are equipped with N_t antennas, while each eavesdropper is equipped with N_e antennas, with all the other nodes possessing a single antenna. Following [24] and [25], it is further assumed that all channels undergo quasi-static flat fading and that the global perfect channel state information (CSI) is available at the

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[1] This noise is also known as AN.

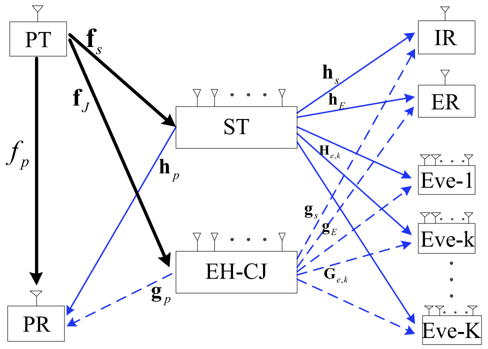

FIGURE 1. System model block diagram. Thick black lines represent the first transmission phase, thin blue lines represent the second transmission phase, solid arrow lines are signal streams, and the dashed arrow lines are interference streams.

transmitter. We also consider the case where Eves are passive, i.e., they listen but do not transmit signals, so that the receiver nodes will not be attacked by the Eves [26].

During the first phase, the PT transmits its data to the PR, so that the received signals at the PR, ST and EH-CJ can be expressed as

$$y_p^{(1)} = f_p x_p + n_p^{(1)} \tag{1}$$

$$\mathbf{y}_r = \mathbf{f}_s x_p + \mathbf{n}_r \tag{2}$$

$$\mathbf{y}_J = \mathbf{f}_J x_p + \mathbf{n}_J \tag{3}$$

respectively, where $x_p \in \mathbb{C}$ is the signal transmitted from the PT and $\mathbb{E}\left[|x_p|^2\right] = P_p$; $f_p \in \mathbb{C}$, $\mathbf{f}_s \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{f}_J \in \mathbb{C}^{N_t \times 1}$ are the complex-valued channel responses from the PT to the PR, to the ST and to the EH-CJ, respectively; $n_p^{(1)}$, $\mathbf{n}_r$ and $\mathbf{n}_J$ are the additive white Gaussian noise (AWGN) components at the PR, the ST and the EH-CJ, distributed as $n_p^{(1)} \sim \mathcal{CN}\left(0, \delta_p^2\right)$, $\mathbf{n}_r \sim \mathcal{CN}\left(\mathbf{0}, \delta_r^2 \mathbf{I}_{N_t}\right)$ and $\mathbf{n}_J \sim \mathcal{CN}\left(\mathbf{0}, \delta_J^2 \mathbf{I}_{N_t}\right)$, respectively.

With the WPT technique, the harvested energy at the EH-CJ can then be represented as

$$E_J = \eta_J \left(P_p \|\mathbf{f}_J\|^2 + N_t \delta_J^2\right) \tag{4}$$

where $\eta_J \in (0, 1]$ is the energy transfer efficiency at the EH-CJ.

During the second phase, the ST acts as a relay to forward the signal intended for the PR while transmitting its own confidential information to its legitimate IR. Therefore, the transmit signal at the ST is given by

$$\mathbf{x} = \mathbf{W}_p \mathbf{y}_r + \mathbf{w}_s x_s \tag{5}$$

where $\mathbf{y}_r \in \mathbb{C}^{N_t \times 1}$ is the received signal vector at the ST intended for the PR, with $\mathbf{y}_r = \mathbf{f}_s x_p + \mathbf{n}_r$; $\mathbf{W}_p$ is the transformation matrix to accomplish the amplify-and-forward (AF) protocol; $x_s \in \mathbb{C}$ is the confidential signal intended for the IR with $\mathbb{E}\left[|x_s^2|\right] = 1$; and $\mathbf{w}_s$ is the beamforming vector to process its own confidential signal x_s. As previous stated, the dimensions of $\mathbf{W}_p$ and $\mathbf{w}_s$ are $N_t \times N_t$ and $N_t \times 1$, respectively. The transmit power at the ST can be expressed as

$$P_r = P_p \left\|\mathbf{W}_p \mathbf{f}_s\right\|^2 + \delta_r^2 \left\|\mathbf{W}_p\right\|^2 + \|\mathbf{w}_s\|^2. \tag{6}$$

Meanwhile, by consuming the energy harvested from the PT, the EH-CJ generates JN, i.e. $\mathbf{z} \in \mathbb{C}^{N_t \times 1}$, to interfere with the Eves in the secondary system, and $\mathbf{z} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{Z}\right)$, where $\mathbf{Z}$ is the JN covariance matrix. Therefore, the transmit power at the EH-CJ can be expressed as

$$P_J = \mathrm{Tr}(\mathbf{Z}) \tag{7}$$

which is constrained by its harvested energy in the first phase.

The signals received at PR, IR, ER and kth eavesdropper Eve-k are, respectively, given by

$$\begin{aligned} y_p^{(2)} &= \mathbf{h}_p^H \mathbf{x} + \mathbf{g}_p^H \mathbf{z} + n_p^{(2)} \\ &= \mathbf{h}_p^H \mathbf{W}_p \mathbf{f}_s x_p + \mathbf{h}_p^H \mathbf{W}_p \mathbf{n}_r + \mathbf{h}_p^H \mathbf{w}_s x_s + \mathbf{g}_p^H \mathbf{z} + n_p^{(2)} \end{aligned} \tag{8}$$

$$\begin{aligned} y_s &= \mathbf{h}_s^H \mathbf{x} + \mathbf{g}_s^H \mathbf{z} + n_s \\ &= \mathbf{h}_s^H \mathbf{W}_p \mathbf{f}_s x_p + \mathbf{h}_s^H \mathbf{W}_p \mathbf{n}_r + \mathbf{h}_s^H \mathbf{w}_s x_s + \mathbf{g}_s^H \mathbf{z} + n_s \end{aligned} \tag{9}$$

$$\begin{aligned} y_E &= \mathbf{h}_E^H \mathbf{x} + \mathbf{g}_E^H \mathbf{z} + n_E \\ &= \mathbf{h}_E^H \mathbf{W}_p \mathbf{f}_s x_p + \mathbf{h}_E^H \mathbf{W}_p \mathbf{n}_r + \mathbf{h}_E^H \mathbf{w}_s x_s + \mathbf{g}_E^H \mathbf{z} + n_E \end{aligned} \tag{10}$$

$$\begin{aligned} \mathbf{y}_{e,k} &= \mathbf{H}_{e,k}^H \mathbf{x} + \mathbf{G}_{e,k}^H \mathbf{z} + \mathbf{n}_{e,k} \\ &= \mathbf{H}_{e,k}^H \mathbf{W}_p \mathbf{f}_s x_p + \mathbf{H}_{e,k}^H \mathbf{W}_p \mathbf{n}_r + \mathbf{H}_{e,k}^H \mathbf{w}_s x_s \\ &\quad + \mathbf{G}_{e,k}^H \mathbf{z} + \mathbf{n}_{e,k}, \quad \forall k \end{aligned} \tag{11}$$

where $\mathbf{h}_p \in \mathbb{C}^{N_t \times 1}$, $\mathbf{h}_s \in \mathbb{C}^{N_t \times 1}$, $\mathbf{h}_E \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{H}_{e,k} \in \mathbb{C}^{N_t \times N_t}$ are the complex-valued channels from the ST to PR, IR, ER and Eve-k, respectively; $\mathbf{g}_p \in \mathbb{C}^{N_t \times 1}$, $\mathbf{g}_s \in \mathbb{C}^{N_t \times 1}$, $\mathbf{g}_E \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{G}_{e,k} \in \mathbb{C}^{N_t \times N_e}$ are the complex-valued channels from the EH-CJ to the PR, the IR, the ER and the Eve-k, respectively; and $n_p^{(2)} \sim \mathcal{CN}\left(0, \delta_p^2\right)$, $n_s \sim \mathcal{CN}\left(0, \delta_s^2\right)$, $n_E \sim \mathcal{CN}\left(0, \delta_E^2\right)$ and $\mathbf{n}_{e,k} \sim \mathcal{CN}\left(\mathbf{0}, \delta_e^2 \mathbf{I}_{N_e}\right)$ are the AWGN components at the PR, the IR, the ER and the Eve-k, respectively.

The harvested energy at the ER can be mathematically expressed as

$$\begin{aligned} E_E = \eta_E (P_p &\left|\mathbf{h}_E^H \mathbf{W}_p \mathbf{f}_s\right|^2 + \delta_r^2 \left\|\mathbf{h}_E^H \mathbf{W}_p\right\|^2 \\ &+ \left|\mathbf{h}_E^H \mathbf{w}_s\right|^2 + \mathbf{g}_E^H \mathbf{Z} \mathbf{g}_E + \delta_E^2) \end{aligned} \tag{12}$$

where $\eta_E \in (0, 1]$ is the energy transfer efficiency at the ER.

Noting that, the JN transmitted from the EH-CJ is treated as noise at the PR, IR and Eves [12]. Assuming the maximal ratio combining (MRC) strategy is employed at the PR to combine the received signals during the two phases [5], the information rate at the PR can be expressed as

$$R_p = \frac{1}{2} \log_2 \left(1 + \frac{P_p |f_p|^2}{\delta_p^2} + \frac{P_p \left|\mathbf{h}_p^H \mathbf{W}_p \mathbf{f}_s\right|^2}{L_p}\right) \tag{13}$$

where $L_p = \delta_r^2 \left\|\mathbf{h}_p^H \mathbf{W}_p\right\|^2 + \left|\mathbf{h}_p^H \mathbf{w}_s\right|^2 + \mathbf{g}_p^H \mathbf{Z} \mathbf{g}_p + \delta_p^2$.

The mutual information of ST-IR and ST-Eve-k is given by

$$R_s = \frac{1}{2}\log_2\left(1+\frac{\left|\mathbf{h}_s^H\mathbf{w}_s\right|^2}{L_s}\right) \tag{14}$$

$$R_{e,k} = \frac{1}{2}\log_2\left|\mathbf{I}_{N_e}+\left|\mathbf{H}_{e,k}^H\mathbf{w}_s\right|^2\mathbf{L}_{e,k}^{-1}\right|, \quad \forall k \tag{15}$$

respectively, where $L_s = P_p\left|\mathbf{h}_s^H\mathbf{W}_p\mathbf{f}_s\right|^2+\delta_r^2\left\|\mathbf{h}_s^H\mathbf{W}_p\right\|^2+\mathbf{g}_s^H\mathbf{Z}\mathbf{g}_s+\delta_s^2$ and $\mathbf{L}_{e,k} = P_p\mathbf{H}_{e,k}^H\mathbf{W}_p\mathbf{f}_s\mathbf{f}_s^H\mathbf{W}_p^H\mathbf{H}_{e,k}+\delta_r^2\mathbf{H}_{e,k}^H\mathbf{W}_p\mathbf{W}_p^H\mathbf{H}_{e,k}+\mathbf{G}_{e,k}^H\mathbf{Z}\mathbf{G}_{e,k}+\delta_e^2\mathbf{I}_{N_e}$. Consequently, the achievable secrecy rate of secondary system is given by [27]

$$R_{\text{sec}} = [R_s-\max_k R_{e,k}]^+, \quad \forall k. \tag{16}$$

III. ACHIEVABLE SECRECY RATE MAXIMIZATION

In the section, we present the details of the considered optimization problem so that the achievable secrecy rate can be maximized. In particular, we first propose the EH-CJ-aided scheme by jointly designing secure beamforming and JN covariance matrix. Then, for comparison purposes, the same optimization problem will be considered by using the isotropic JN scheme.

A. EH-CJ-AIDED SCHEME: JOINTLY DESIGN OF SECURE BEAMFORMING AND JN COVARIANCE MATRIX

The aim here is to jointly design the beamforming matrix $\mathbf{W}_p$, beamforming vector $\mathbf{w}_s$ and JN covariance matrix $\mathbf{Z}$ for maximizing the achievable secrecy rate of the secondary system subject to the following constraints: i) Transmit power at the ST and the EH-CJ; ii) Harvested energy at the ER; iii) Information rate at the PR. Mathematically this very complex optimization problem can be formulated as

$$\begin{aligned}
&\max_{\mathbf{W}_p,\mathbf{w}_s,\mathbf{Z}} R_{\text{sec}}\\
&\text{s.t. } P_r \le P_{pre}\\
&\qquad P_J \le E_J\\
&\qquad E_E \ge E_{pre}\\
&\qquad R_p \ge R_{pre}\\
&\qquad \mathbf{Z} \succeq 0
\end{aligned} \tag{17}$$

where $P_{pre} > 0$ represents the maximum available transmit power at the ST; $E_{pre} > 0$ denotes the minimum amount of harvested energy at the ER; and $R_{pre} > 0$ is the minimum information rate requirement at the PR.

Since this optimization problem is non-convex, we first introduce a slack variable β and reformulate (17) as

$$\max_{\mathbf{W}_p,\mathbf{w}_s,\mathbf{Z},\beta} \log_2\left(1+\frac{\left|\mathbf{h}_s^H\mathbf{w}_s\right|^2}{L_s}\right)-\log_2(\frac{1}{\beta})$$

$$\text{s.t. } \max_k \det\left(\mathbf{I}_{N_e}+\mathbf{H}_{e,k}^H\mathbf{w}_s\mathbf{w}_s^H\mathbf{H}_{e,k}\mathbf{L}_{e,k}^{-1}\right)\le\frac{1}{\beta}, \quad \forall k \tag{18a}$$

$$P_p\left\|\mathbf{W}_p\mathbf{f}_s\right\|^2+\delta_r^2\left\|\mathbf{W}_p\right\|^2+\|\mathbf{w}_s\|^2\le P_{pre} \tag{18b}$$

$$\text{Tr}(\mathbf{Z})\le\eta_J(P_p\|\mathbf{f}_J\|^2+N_t\delta_J^2) \tag{18c}$$

$$\eta_E(P_p\left|\mathbf{h}_E^H\mathbf{W}_p\mathbf{f}_s\right|^2+\delta_r^2\left\|\mathbf{h}_E^H\mathbf{W}_p\right\|^2+\left|\mathbf{h}_E^H\mathbf{w}_s\right|^2 + \mathbf{g}_E^H\mathbf{Z}\mathbf{g}_E+\delta_E^2)\ge E_{pre} \tag{18d}$$

$$P_p\left|\mathbf{h}_p^H\mathbf{W}_p\mathbf{f}_s\right|^2L_p^{-1}\ge\gamma \tag{18e}$$

$$\mathbf{Z}\succeq 0 \tag{18f}$$

where $\gamma = 2^{2R_{pre}}-1-P_p\left|f_p\right|^2\delta_p^{-2}$. Furthermore, due to the constraint of (18a), we employ a two-stage optimization approach to solve it. Specifically, the outer optimization problem is a function of β, which can be written as

$$\begin{aligned}
&\max_\beta \ \log_2(1+f(\beta))-\log_2(\frac{1}{\beta})\\
&\text{s.t. } \beta_{\min}\le\beta\le 1
\end{aligned} \tag{19}$$

where the lower bound of β is derived from the fact that the objective function is nonnegative, i.e. $\beta_{\min} = \left(1+P_{pre}|\mathbf{h}_s|^2\delta_s^{-2}\right)^{-1}$. Note that this outer problem is a function of β, and it can be solved using a one-dimensional line search algorithm.

For a given β, the inner problem can be expressed as

$$\begin{aligned}
f(\beta) = &\max_{\mathbf{W}_p,\mathbf{w}_s,\,\mathbf{Z}} \frac{\left|\mathbf{h}_s^H\mathbf{w}_s\right|^2}{L_s}\\
&\text{s.t. } (18a)-(18f).
\end{aligned} \tag{20}$$

In order to facilitate the optimization problem given in (20), the following parameters are introduced

$$\begin{aligned}
&\mathbf{w}_p = \text{vec}(\mathbf{W}_p),\ \mathbf{X} = \mathbf{w}_s\mathbf{w}_s^H,\ \mathbf{Y} = \mathbf{w}_p\mathbf{w}_p^H,\\
&\mathbf{M} = (\mathbf{f}_s^T\otimes\mathbf{I})\mathbf{Y}(\mathbf{f}_s^T\otimes\mathbf{I})^H,\\
&\mathbf{B} = \text{BD}(\mathbf{1}_{N_t\times N_t},\mathbf{1}_{N_t\times N_t},\cdots\mathbf{1}_{N_t\times N_t}),\\
&\mathbf{N} = (\mathbf{1}_{N_t\times 1}\otimes\mathbf{I})^T(\mathbf{B}\odot\mathbf{Y})(\mathbf{1}_{N_t\times 1}\otimes\mathbf{I}),\\
&\mathbf{F} = P_p\left(\mathbf{f}_s^*\mathbf{f}_s^T\otimes\mathbf{I}_{N_t}\right)+\delta_r^2\mathbf{I}_{N_t^2},\\
&\mathbf{Q}_1 = P_p\mathbf{M}+\delta_r^2\mathbf{N},\\
&\mathbf{Q}_2 = P_p\mathbf{M}+\delta_r^2\mathbf{N}+\mathbf{X},\\
&\mathbf{Q}_3 = P_p\mathbf{M}-\gamma\delta_r^2\mathbf{N}-\gamma\mathbf{X}.
\end{aligned} \tag{21}$$

Then, by substituting (21) into (20), the inner problem can be reformulated as

$$\begin{aligned}
&\max_{\mathbf{X},\mathbf{Y},\mathbf{Z}} \ \frac{\mathbf{h}_s^H\mathbf{X}\mathbf{h}_s}{\mathbf{h}_s^H\mathbf{Q}_1\mathbf{h}_s+\mathbf{g}_s^H\mathbf{Z}\mathbf{g}_s+\delta_s^2}\\
&\text{s.t. } \max_k\left(\beta^{-1}-1\right)(\delta_e^2\mathbf{I}_{N_e}+\mathbf{H}_{e,k}^H\mathbf{Q}_1\mathbf{H}_{e,k}\\
&\qquad +\mathbf{G}_{e,k}^H\mathbf{Z}\mathbf{G}_{e,k})-\mathbf{H}_{e,k}^H\mathbf{X}\mathbf{H}_{e,k}\succeq 0, \quad \forall k\\
&\qquad \text{Tr}(\mathbf{F}\mathbf{Y})+\text{Tr}(\mathbf{X})\le P_{pre}\\
&\qquad \text{Tr}(\mathbf{Z})\le\eta_J(P_p\text{Tr}\left(\mathbf{f}_J\mathbf{f}_J^H\right)+N_t\delta_J^2)\\
&\qquad \mathbf{h}_E^H\mathbf{Q}_2\mathbf{h}_E+\mathbf{g}_E^H\mathbf{Z}\mathbf{g}_E+\delta_E^2-\eta_E^{-1}E_{pre}\ge 0\\
&\qquad \mathbf{h}_p^H\mathbf{Q}_3\mathbf{h}_p-\gamma\mathbf{g}_p^H\mathbf{Z}\mathbf{g}_p-\gamma\delta_p^2\ge 0\\
&\qquad \mathbf{X}\succeq 0,\ \ \mathbf{Y}\succeq 0, \mathbf{Z}\succeq 0\\
&\qquad \text{rank}\,(\mathbf{X}) = 1, \quad \text{rank}\,(\mathbf{Y}) = 1
\end{aligned} \tag{22}$$

where the first inequality constraint in (22) can be derived by applying [27, Proposition 1]. The inner problem is still non-convex due to the linear fractional objective function and rank-one constraints. Thus, the use of the Charnes-Cooper transformation [28] and rank-one relaxation converts the inner problem into a convex semidefinite program (SDP) problem. By introducing the following variables

$$\mathbf{X}=\widetilde{\mathbf{X}}/\mu,\quad \mathbf{Y}=\widetilde{\mathbf{Y}}/\mu,\ \mathbf{Z}=\widetilde{\mathbf{Z}}/\mu,\ \mu\geq 0 \tag{23}$$

the inner problem is equivalently formulated as

$$\begin{aligned}
\max_{\widetilde{\mathbf{X}},\widetilde{\mathbf{Y}},\widetilde{\mathbf{Z}},\mu\geq 0}\ & \mathrm{Tr}(\widetilde{\mathbf{X}}\mathbf{h}_s\mathbf{h}_s^H)\\
\text{s.t. } & \mathrm{Tr}(\widetilde{\mathbf{Q}}_1\mathbf{h}_s\mathbf{h}_s^H)+\mathrm{Tr}(\widetilde{\mathbf{Z}}\mathbf{g}_s\mathbf{g}_s^H)+\mu\delta_s^2=1\\
& \max_k \left(\beta^{-1}-1\right)(\mu\delta_e^2\mathbf{I}_{N_e}+\mathbf{H}_{e,k}^H\widetilde{\mathbf{Q}}_1\mathbf{H}_{e,k}\\
&\quad +\mathbf{G}_{e,k}^H\widetilde{\mathbf{Z}}\mathbf{G}_{e,k})-\mathbf{H}_{e,k}^H\widetilde{\mathbf{X}}\mathbf{H}_{e,k}\succeq 0,\ \forall k\\
& \mathrm{Tr}(\mathbf{F}\widetilde{\mathbf{Y}})+\mathrm{Tr}(\widetilde{\mathbf{X}})\leq \mu P_{pre}\\
& \mathrm{Tr}(\widetilde{\mathbf{Z}})\leq \mu\eta_J\left(P_p\mathrm{Tr}\left(\mathbf{f}_J\mathbf{f}_J^H\right)+N_t\delta_J^2\right)\\
& \mathrm{Tr}(\widetilde{\mathbf{Q}}_2\mathbf{h}_E\mathbf{h}_E^H)+\mathrm{Tr}(\widetilde{\mathbf{Z}}\mathbf{g}_E\mathbf{g}_E^H)\geq \mu(\eta_E^{-1}E_{pre}-\delta_E^2)\\
& \mathrm{Tr}(\widetilde{\mathbf{Q}}_3\mathbf{h}_p\mathbf{h}_p^H)-\gamma\mathrm{Tr}(\widetilde{\mathbf{Z}}\mathbf{g}_p\mathbf{g}_p^H)-\mu\gamma\delta_p^2\geq 0\\
& \widetilde{\mathbf{X}}\succeq 0,\quad \widetilde{\mathbf{Y}}\succeq 0,\ \widetilde{\mathbf{Z}}\succeq 0.
\end{aligned} \tag{24}$$

For a given β, the optimization problem in (24) is a standard convex SDP, which can be efficiently solved using some existing software packages, e.g., CVX [29]. Clearly, when the optimal solution $\left(\widetilde{\mathbf{X}}^*,\widetilde{\mathbf{Y}}^*,\widetilde{\mathbf{Z}}^*,\mu^*\right)$ to problem in (24) is derived, the solution $(\mathbf{X}^*,\mathbf{Y}^*,\mathbf{Z}^*)$ can be obtained via

$$\mathbf{X}^*=\widetilde{\mathbf{X}}^*/\mu^*,\quad \mathbf{Y}^*=\widetilde{\mathbf{Y}}^*/\mu^*,\ \mathbf{Z}^*=\widetilde{\mathbf{Z}}^*/\mu^*. \tag{25}$$

Since the rank-one constraint has been dropped, therefore if $\mathbf{X}^*$ and $\mathbf{Y}^*$ satisfy the rank-one constraint, $(\mathbf{X}^*,\mathbf{Y}^*,\mathbf{Z}^*)$ is the optimal solution to (22). In this way, the optimal beamforming matrix $\mathbf{W}_p^*$ and beamforming vector $\mathbf{w}_s^*$ can be acquired through eigenvalue decomposition, and the optimal JN covariance matrix $\mathbf{Z}^*$ is derived. If $\mathrm{rank}\,(\mathbf{X}^*)>1$ and $\mathrm{rank}\,(\mathbf{Y}^*)>1$, the Gaussian randomization procedure can be used to derive $\mathbf{W}_p^*$ and $\mathbf{w}_s^*$ [30].

B. ISOTROPIC JN SCHEME: JOINTLY DESIGN SECURE BEAMFORMING BASED ON ISOTROPIC JN

In order to evaluate the proposed EH-CJ-aided scheme fairly, its performance should be compared with that of an equivalent isotropic JN scheme. Note that the JN transmitted from the EH-CJ interferes the eavesdroppers' reception, as well as degrades the signal quality at both the PR and the IR. To avoid the interference caused to both the PR and IR by the EH-CJ, we employ the null-space scheme. Specifically, isotropic JN is distributed in the null space of the channels from the EH-CJ to the PR and IR with the assumption that $N_t>2$. In this way, the JN transmitted from the EH-CJ can be expressed as

$$\mathbf{z}=\mathbf{G}^{\perp}\mathbf{n}_z \tag{26}$$

where $\mathbf{G}^{\perp}=\mathbf{I}-\mathbf{G}\left(\mathbf{G}^H\mathbf{G}\right)^{-1}\mathbf{G}^H$ denotes the orthogonal complement projector of $\mathbf{G}=[\mathbf{g}_p\ \mathbf{g}_s]$, and $\mathbf{n}_z\sim\mathcal{CN}\left(\mathbf{0},\sigma_z^2\mathbf{I}\right)$. Then, the transmit power at the EH-CJ is

$$P_J=\mathrm{Tr}(\mathbf{Z})=(N_t-2)\,\sigma_z^2. \tag{27}$$

Obviously, both the harvested energy at the ER and the interference power at the Eves are monotonic increasing functions with respect to the parameter σ_z^2. Therefore, the value of σ_z^2 is derived as

$$\sigma_z^2=\eta_J\left(P_p\|\mathbf{f}_J\|^2+N_t\delta_J^2\right)\Big/(N_t-2). \tag{28}$$

We jointly design the beamforming matrix and beamforming vector based on isotropic JN. By letting $\Psi_{e,k}=\mathbf{G}_{e,k}^H\mathbf{G}^{\perp}$ and $\mathbf{L}_E=\mathbf{g}_E^H\mathbf{G}^{\perp}$, the inner problem can then be reformulated as

$$\begin{aligned}
\max_{\mathbf{X},\mathbf{Y}}\ & \frac{\mathbf{h}_s^H\mathbf{X}\mathbf{h}_s}{\mathbf{h}_s^H\mathbf{Q}_1\mathbf{h}_s+\delta_s^2}\\
\text{s.t. } & \max_k \left(\beta^{-1}-1\right)(\delta_e^2\mathbf{I}_{N_e}+\mathbf{H}_{e,k}^H\mathbf{Q}_1\mathbf{H}_{e,k}\\
&\quad +\sigma_z^2\Psi_{e,k}\Psi_{e,k}^H)-\mathbf{H}_{e,k}^H\mathbf{X}\mathbf{H}_{e,k}\succeq 0,\quad \forall k\\
& \mathrm{Tr}(\mathbf{F}\mathbf{Y})+\mathrm{Tr}(\mathbf{X})\leq P_{pre}\\
& \mathbf{h}_E^H\mathbf{Q}_2\mathbf{h}_E+\sigma_z^2\mathbf{L}_E\mathbf{L}_E^H+\delta_E^2-\eta_E^{-1}E_{pre}\geq 0\\
& \mathbf{h}_p^H\mathbf{Q}_3\mathbf{h}_p-\gamma\delta_p^2\geq 0\\
& \mathbf{X}\succeq 0,\ \mathbf{Y}\succeq 0\\
& \mathrm{rank}\,(\mathbf{X})=1,\ \mathrm{rank}\,(\mathbf{Y})=1.
\end{aligned} \tag{29}$$

By employing the Charnes-Cooper transformation and rank-one relaxation, the optimization problem given in (29) can be expressed as

$$\begin{aligned}
\max_{\widetilde{\mathbf{X}},\widetilde{\mathbf{Y}},\mu\geq 0}\ & \mathrm{Tr}(\widetilde{\mathbf{X}}\mathbf{h}_s\mathbf{h}_s^H)\\
\text{s. t. } & \mathrm{Tr}(\widetilde{\mathbf{Q}}_1\mathbf{h}_s\mathbf{h}_s^H)+\mu\delta_s^2=1\\
& \max_k \left(\beta^{-1}-1\right)(\mu\delta_e^2\mathbf{I}_{N_e}+\mathbf{H}_{e,k}^H\widetilde{\mathbf{Q}}_1\mathbf{H}_{e,k}\\
&\quad +\mu\sigma_z^2\Psi_{e,k}\Psi_{e,k}^H)-\mathbf{H}_{e,k}^H\widetilde{\mathbf{X}}\mathbf{H}_{e,k}\succeq 0,\quad \forall k\\
& \mathrm{Tr}(\mathbf{F}\widetilde{\mathbf{Y}})+\mathrm{Tr}(\widetilde{\mathbf{X}})\leq \mu P_{pre}\\
& \mathrm{Tr}(\widetilde{\mathbf{Q}}_2\mathbf{h}_E\mathbf{h}_E^H)+\mu\sigma_z^2\mathrm{Tr}(\mathbf{L}_E^H\mathbf{L}_E)\geq \mu(\eta_E^{-1}E_{pre}-\delta_E^2)\\
& \mathrm{Tr}(\widetilde{\mathbf{Q}}_3\mathbf{h}_p\mathbf{h}_p^H)-\mu\gamma\delta_p^2\geq 0\\
& \widetilde{\mathbf{X}}\succeq 0,\ \widetilde{\mathbf{Y}}\succeq 0.
\end{aligned} \tag{30}$$

It can be easily seen that the optimization problem given in (30) is convex SDP and can be solved similarly to the optimization problem given in (24) by employing off-the-shelf solvers, such as CVX [29].

IV. PERFORMANCE EVALUATION RESULTS AND DISCUSSION

The performance of the proposed scheme has been evaluated by means of computer simulations using the following assumptions as well as specific values for the various system parameters. For the channel, we have considered the case where all channel responses are composed of independent identically distributed Rayleigh fading with path losses $d^{-\frac{\alpha}{2}}$ ($\alpha=3.5$), while the distance between the ST/EH-CJ and all other nodes was the same (1.5 m), and the distance between the PT and the PR was 2 m. The noise variances at all the receivers were assumed to be 0.5 mW. Moreover, and unless otherwise stated, $N_t = 4$, $N_e = 3$, $\eta_J = \eta_E = 0.8$, the target transmission rate at the PR was selected to be $R_{pre} = 2$ bps/Hz, and the minimum harvested energy at the ER was $E_{pre} = 5$ dBm. The optimization problems have been solved by using the CVX toolbox, and the performance evaluation results, which will be presented next, have been obtained by running an average of about 1000 Monte-Carlo computer simulation experiments.

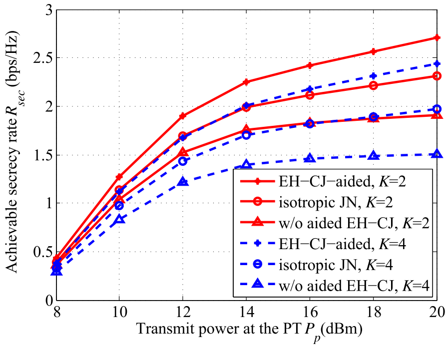

FIGURE 2. **Performance evaluation results for R_{sec} vs. P_p for the three schemes under consideration with $K = 2$ and 4.**

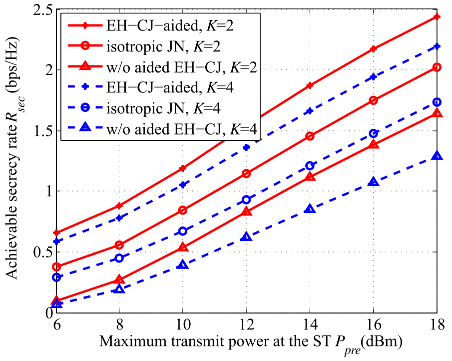

FIGURE 3. **Performance evaluation results for R_{sec} vs. P_{pre} for the three schemes under consideration with $K = 2$ and 4.**

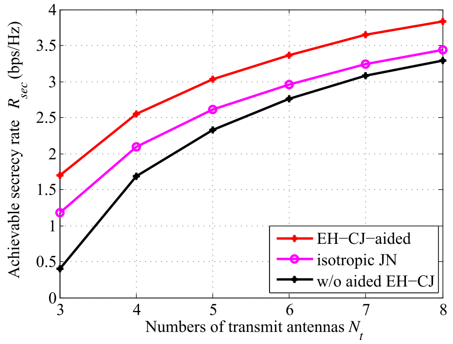

FIGURE 4. **R_{sec} performance evaluation as a function of N_t for the three communication systems under consideration.**

In Figs. 2-4, where the various performance evaluation are presented, the proposed EH-CJ-aided scheme and isotropic JN scheme are labeled as "EH-CJ-aided" and "isotropic JN", respectively, while the scheme without the aid of EH-CJ is labeled as "w/o aided EH-CJ". For the latter scheme, its performance results were obtained by solving the optimization problem given in (17) with $\mathbf{Z} = \mathbf{0}$.

Figs. 2 and 3 present the performance evaluation results of R_{sec} vs. P_p and R_{sec} vs. P_{pre}, respectively, of the three schemes under consideration for $K = 2$ and $K = 4$. In Fig. 2, the predefined transmit power at the ST is fixed at $P_{pre} = 20$ dBm. These results clearly show that the achievable secrecy rate increases as P_p increases, while the performance gain increases slowly when P_p is larger. Furthermore, the performance gap between the EH-CJ-aided scheme and the other two schemes is more evident as P_p increases. Note that, in obtaining the performance results shown in Fig. 3, the transmit power at the PT was fixed at $P_p = 20$ dBm. It can be seen from these performance evaluation results that the achievable secrecy rate increases as P_{pre} increases. This happens because with increasing P_{pre}, there is more energy that can be used at the ST to improve the achievable secrecy rate. From both of the these figures, it is also observed that the achievable secrecy rate decreases with K, and the proposed EH-CJ-aided scheme can always achieve better secrecy rate performance than both the isotropic JN scheme and the scheme without the aid of EH-CJ.

In Fig. 4, we present the performance of R_{sec} vs. N_t, which was obtained for $P_p = 20$ dBm and $P_{pre} = 20$ dBm, while the number of Eves was $K = 3$. These results clearly show that the achievable secrecy rate increases as N_t increases. This observation is in agreement with the fact that multiple transmit antennas can provide spatial degree of freedom to enhance the secrecy performance. It can be also observed that the achievable secrecy rate difference between the EH-CJ-aided and without the aid of EH-CJ schemes becomes smaller as N_t increases, which leads to the conclusion that less JN is required when the degree of freedom increases. In addition, the obtained performance evaluation results confirm the superiority of the proposed EH-CJ-aided scheme since it always yields better secrecy rate performance as compared to the performance of the other two schemes.

V. CONCLUSIONS

A novel wireless EH-CJ-aided secure transmission scheme for CCRNs in the presence of multiple multi-antenna eavesdroppers has been presented. With the aim of maximizing the achievable secrecy rate of the secondary system, subject to power constraints at the ST and the EH-CJ, minimum harvested energy constraint at the secondary ER and information rate constraint at the PR, we have jointly designed the retransmit beamforming matrix for the PT's signal and transmit beamforming vector for the ST's signal at the ST, and the JN covariance matrix at the EH-CJ. Various performance evaluation results obtained by means of Monte-Carlo computer simulation experiments have verified that the proposed scheme can always achieve better secrecy rate performance as compared to the isotropic JN scheme and the scheme without the aid of EH-CJ.

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REFERENCES

[1] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Apr. 1999.

[2] G. Zheng, I. Krikidis, and B. Ottersten, "Full-duplex cooperative cognitive radio with transmit imperfections," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2498–2511, May 2013.

[3] G. Zheng, S. Song, K.-K. Wong, and B. Ottersten, "Cooperative cognitive networks: Optimal, distributed and low-complexity algorithms," *IEEE Trans. Signal Process.*, vol. 61, no. 11, pp. 2778–2790, Jun. 2013.

[4] Q. Li, Q. Zhang, and J. Qin, "Beamforming for information and energy cooperation in cognitive non-regenerative two-way relay networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5302–5313, Aug. 2016.

[5] G. Zheng, Z. Ho, E. A. Jorswieck, and B. Ottersten, "Information and energy cooperation in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 62, no. 9, pp. 2290–2303, May 2014.

[6] R. K. Sharma and D. B. Rawat, "Advances on security threats and countermeasures for cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 1023–1043, 2nd Quart., 2015.

[7] A. D. Wyner, "The wire-tap channel," *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, 1975.

[8] Q. Li and W.-K. Ma, "Optimal and robust transmit designs for MISO channel secrecy by semidefinite programming," *IEEE Trans. Signal Process.*, vol. 59, no. 8, pp. 3799–3812, Aug. 2011.

[9] R. Negi and S. Goel, "Secret communication using artificial noise," in *Proc. IEEE Veh. Tech. Conf.*, Dallas, TX, USA, Sep. 2005, pp. 1906–1910.

[10] Y. He, J. Evans, and S. Dey, "Secrecy rate maximization for cooperative overlay cognitive radio networks with artificial noise," in *Proc. IEEE Int. Conf. Commun.*, Sydney, NSW, Australia, Jun. 2014, pp. 1663–1668.

[11] F. Zhu and M. Yao, "Improving physical-layer security for CRNs using SINR-based cooperative beamforming," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1835–1841, Mar. 2016.

[12] S. A. A. Fakoorian and A. L. Swindlehurst, "Solutions for the MIMO Gaussian wiretap channel with a cooperative jammer," *IEEE Trans. Signal Process.*, vol. 59, no. 10, pp. 5013–5022, Oct. 2011.

[13] N. Zhang, N. Lu, N. Cheng, J. W. Mark, and X. S. Shen, "Cooperative spectrum access towards secure information transfer for CRNs," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2453–2464, Nov. 2013.

[14] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[15] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.

[16] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 117–125, Apr. 2015.

[17] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[18] H. Xing, K.-K. Wong, Z. Chu, and A. Nallanathan "To harvest and jam: A paradigm of self-sustaining friendly jammers for secure AF relaying," *IEEE Trans. signal Process.*, vol. 63, no. 24, pp. 6616–6631, Dec. 2015.

[19] A. El Shafie, D. Niyato, and N. Al-Dhahir, "Artificial-noise-aided secure MIMO full-duplex relay channels with fixed-power transmissions," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1591–1594, Aug. 2016.

[20] J. Moon, H. Lee, C. Song, and I. Lee, "Secrecy performance optimization for wireless powered communication networks with an energy harvesting jammer," *IEEE Trans. Commun.*, vol. 65, no. 2, pp. 764–774, Feb. 2017.

[21] F. Zhou, Z. Li, J. Cheng, Q. Li, and J. Si, "Robust AN-aided beamforming and power splitting design for secure MISO cognitive radio with SWIPT," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2450–2464, Apr. 2017.

[22] Y. Wu and X. Chen, "Robust beamforming and power splitting for secrecy wireless information and power transfer in cognitive relay networks," *IEEE Commun. Lett.*, vol. 20, no. 6, pp. 1152–1155, Jun. 2016.

[23] L. Jiang, H. Tian, C. Qin, S. Gjessing, and Y. Zhang, "Secure beamforming in wireless-powered cooperative cognitive radio networks," *IEEE Commun. Lett.*, vol. 20, no. 3, pp. 522–525, Mar. 2016.

[24] X. Zhao, J. Xiao, Q. Li, Q. Zhang, and J. Qin, "Joint optimization of an-aided transmission and power splitting for MISO secure communications with SWIPT," *IEEE Commun. Lett.*, vol. 19, no. 11, pp. 1969–1972, Nov. 2015.

[25] T. Zhang, Y. Huang, Y. Cai, C. Zhong, W. Yang, and G. K. Karagiannidis, "Secure multiantenna cognitive wiretap networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4059–4072, May 2017.

[26] X. Zhou and M. R. McKay, "Secure transmission with artificial noise over fading channels: Achievable rate and optimal power allocation," *IEEE Trans. Veh. Technol.*, vol. 59, no. 8, pp. 3831–3842, Oct. 2010.

[27] Q. Li and W.-K. Ma, "Spatially selective artificial-noise aided transmit optimization for MISO multi-eves secrecy rate maximization," *IEEE Trans. Signal Process.*, vol. 61, no. 10, pp. 2704–2717, May 2013.

[28] A. Charnes and W. W. Cooper, "Programming with linear fractional functionals," *Naval Res. Logistics Quart.*, vol. 9, nos. 3–4, pp. 181–186, 1962.

[29] M. Grant and S. P. Boyd. *CVX: MATLAB Software for Disciplined Convex Programming*. Accessed: Dec. 2017. [Online]. Available: http://cvxr.com/cvx

[30] Z.-Q. Luo, W.-K. Ma, A. M.-C. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Process. Mag.*, vol. 27, no. 3, pp. 20–34, May 2010.

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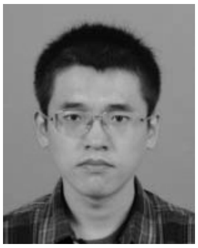

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