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Robust AN-Aided Beamforming Design for Secure MISO Cognitive Radio Based on a Practical Nonlinear EH Model

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ABSTRACT  Energy harvesting techniques are promising in next generation wireless communication systems. However, most of the existing works are based on an ideal linear energy harvesting model. In this paper, a multiple-input single-output cognitive radio network is studied under a practical non-linear energy harvesting model. In order to improve the security of both the primary network and the secondary network, a cooperative jamming scheme is proposed. A robust artificial noise aided beamforming design problem is formulated under the bounded channel state information error model. The formulated problem is non-convex and challenging to be solved. Using S-Procedure and the semidefinite relaxation method, a suboptimal beamforming can be obtained. Simulation results show that the performance achieved under the non-linear energy harvesting model may be better than that obtained under the linear energy harvesting model. It is also shown that the cooperation between the primary network and the secondary network can obtain a performance gain compared with that without this cooperation.

INDEX TERMS  Energy harvesting, non-linear energy harvesting model, physical-layer secrecy, robust beamforming.

I. INTRODUCTION

The Internet of Things (IoT) has been recognized as a promising technique for promoting the development of the smart city [1]. It consists of large numbers of sensors, which are powered by batteries that only have limited energy storage capacity. The limited energy storage capacity cannot perpetuate the lifetime of IoT. Fortunately, energy harvesting (EH) techniques have been proposed to provide prospective schemes for addressing this issue [2]. Particularly, radio frequency signals are exploited as sources for powering the energy-limited devices. There are two different research lines on energy harvesting. One is the investigation on the wireless powered communication networks (WPCN) [3]–[5]. In WPCN, a so-called harvest-then-transmit protocol is adopted. The other is the focus on simultaneous wireless information and power transfer (SWIPT) [6]–[8]. The energy and information can be simultaneously transmitted by using SWIPT techniques.

Besides the energy issue, the spectrum scarcity problem is another bottleneck for the development of IoT due to the explosive increase of communication devices. Moreover, the current fixed spectrum allocation strategy has resulted in a low spectrum utilization efficiency [9]–[12]. To alleviate the spectrum scarcity problem, cognitive radio (CR) has been proposed [9]. In CR, the secondary network can coexist with the primary network on the condition that the interference imposed on the primary user (PU) is tolerable. There are three operation paradigms in CR, namely, opportunistic spectrum access, sensing-based spectrum sharing and spectrum sharing [13]. In this paper, we focus on the spectrum sharing paradigm due to its easy implementation in practice.
It is envisioned that the integration of energy harvesting techniques into CR can simultaneously improve the energy efficiency and the spectrum efficiency [14], [15]. This integration has been identified as a promising candidate for the future wireless communication systems. However, due to the broadcasting nature of CR and the dual function of radio frequency signals, CR with energy harvesting is vulnerable to be eavesdropped [16]–[21]. Thus, the security of CR with energy harvesting is of great importance.

Recently, an emerging technique called physical-layer security has been proposed to improve the security of the wireless communication systems [16]–[18]. It exploits the channel characteristic to achieve secure communication. However, the secrecy rate achieved by using physical-layer security is limited by the channel state information (CSI) [16]–[21]. In this paper, in order to improve the security of a CR with SWIPT, a cooperative protocol and an artificial noise (AN)-aided transmit strategy are proposed based on a practical non-linear EH model.

A. RELATED WORK AND MOTIVATION

Due to the broadcasting nature of CR, malicious secondary users can illegitimately access the spectrum bands of the primary users and change the spectrum environment [19]. As a result, the secondary network cannot coexist with the primary network. In order to improve the security of CR, authors in [19]–[24] have done many excellent investigations focusing on physical-layer security techniques. In [19], multiple-antennas techniques have been exploited and an optimal transmission covariance matrix has been designed to maximize the secrecy rate of multiple-input single-output (MISO) CR. It was shown that multiple antennas techniques are efficient to improve the security of CR. Based on the work in [19], authors in [20] and [21] have considered practical and imperfect CSI and designed robust optimal precoding schemes. In [22], the secrecy rate maximization problem was extended into MISO CR and the fading channel was considered. In [20]–[22], the bounded CSI error model was applied and a safe result was obtained. In order to improve the performance obtained under the bounded CSI error model, authors in [23] considered a robust beamforming design problem in MISO CR under the probabilistic CSI error model. It was shown that a secrecy rate gain can be obtained under the probabilistic CSI error model at the cost of a high computation complexity. Recently, in [24] studied robust beamforming design problems in multicast CR.

Since energy harvesting techniques have not been considered in the works in [19]–[24], the resource allocation schemes proposed in these works are inappropriate in CR with energy harvesting. Recently, investigations performed in [25]–[30] have designed optimal resource allocation schemes for CR while SWIPT techniques are applied. In [25], an AN-aided precoding scheme was designed to maximize the secrecy rate of the secondary user while considered the energy requirement of energy harvesting receivers (EHRs). However, it was assumed that the perfect CSI can be obtained. In practice, it is extremely difficult to obtain an accurate CSI. Under the bounded CSI error model, the authors in [26] studied the sum harvesting power maximization problem in multiple-input multiple-output (MIMO) CR with SWIPT. In order to further improve the secrecy rate of SUs, AN-aided beamforming schemes were designed for MISO CR with SWIPT where both the bounded CSI error model and the probabilistic CSI error model were adopted. From the perspective of multiple-objects optimization, three multiple-objects optimization problems were studied in MISO CR with SWIPT in [28]. The authors in [29] jointly optimized the AN-aided beamforming and power splitting designs to minimize the transmit power while considered statistical channel uncertainties. In [30], authors proposed a robust beamforming scheme by studying an outage-constrained secrecy rate maximization problem in MIMO CR with SWIPT.

However, the works in [25]–[30] adopted an ideal linear energy harvesting model. Under this model, the harvesting energy linearly increases with the input power. Since the practical power conversion circuit results in a non-linear end-to-end wireless power transfer, the harvesting energy is non-linear. Thus, resource allocation schemes proposed in [25]–[28] may be inefficient in practice. In order to address this issue, authors in [31]–[35] proposed two non-linear EH models and designed optimal resource allocation strategies in different scenarios. In [31], the outage performance was analyzed in wireless-powered relaying MIMO systems where a non-linear energy model was considered. In this model, the harvesting energy firstly increases with the input power, and then achieves the maximum value when the input power is large. In [32]–[35], a new non-linear EH model was proposed. Based on this model, the sum harvesting energy was maximized by designing an optimal beamforming scheme [32]. It was shown that a performance gain can be achieved under the non-linear EH model compared with the linear EH model. Recently, considering the bounded CSI error model, the sum harvesting energy maximization problems were extended into MISO systems with SWIPT and wireless powered MIMO systems in [33] and [34], respectively. It was also shown that the practical non-linear EH model has superiority in performance.

In [31]–[34], the transmission security was not considered. However, since the radio frequency signal carries confidential information, it is susceptible to be intercepted. In order to guarantee the security of SWIPT systems, authors in [35] designed an optimal AN-aided beamforming scheme based on physical-layer security techniques. However, the resource scheme proposed in [35] was inadequate to CR with SWIPT. In CR with SWIPT, the mutual interference between the primary network and the secondary network should be considered. Up to now, to the authors’ best knowledge, no investigations have been done for the secure issue in CR with SWIPT where a practical nonlinear energy harvesting model is considered. Thus, in this paper, a robust resource allocation problem is studied in CR with SWIPT and the practical non-linear EH model proposed in [32]–[35] is applied.
B. CONTRIBUTIONS AND ORGANIZATION

In this paper, in order to improve the security of both the primary network and the secondary network, a robust resource allocation problem is investigated in MISO CR with SWIPT. Note that our work is different from the work in [27]. The main differences are as follows. In this paper, the security of both the primary network and the secondary network is improved while only the security of the secondary network is considered in [27]. Moreover, a linear EH model was adopted in [27] while a practical non-linear EH is exploited in this work. The main contributions are summarized as follows.

1) An AN-aided cooperative scheme is proposed to improve the security of both the primary network and the secondary network. In this scheme, the primary network allows the secondary network to access its spectrum band. And in return, the cognitive base station (CBS) transmits a jamming signal to improve the security of the primary network.

2) Considering a practical non-linear EH model, a power minimization problem is formulated in MISO CR with SWIPT where a bounded CSI error model is applied. The problem is nonconvex and challenging. A suboptimal resource allocation scheme is designed by using auxiliary variables and semidefinite program (SDP) methods.

3) Simulation results show that the performance obtained under the practical non-linear EH model may be better than that achieved under the linear EH model. It is also shown that the required transmit power increases with the CSI error. Moreover, simulation results demonstrate that a performance gain can be obtained by using our proposed cooperation scheme compared with that scheme without cooperation between the primary network and the secondary network.

The remainder of this paper is organized as follows. Section II presents the system model. A robust resource allocation problem is formulated in Section III. Section IV presents simulation results. The paper concludes with Section V.

Notations: Vectors and matrices are denoted by boldface lower case letters and boldface capital letters, respectively. \( A \) represents the identity matrix; The Hermitian (conjugate) transpose, trace, and rank of a matrix \( A \) are represented respectively by \( A^H \), \( \text{Tr}(A) \) and \( \text{Rank}(A) \). \( x^N \) denotes the conjugate transpose of a vector \( x \). \( \mathbb{C}^{M \times N} \) denotes a \( M \)-by-\( N \) dimensional complex matrix set. \( A \succeq 0 \) (\( A > 0 \)) represents that \( A \) is a Hermitian positive semidefinite (definite) matrix. \( \mathbb{H}^N \) and \( \mathbb{H}_+^N \) denotes a \( N \)-by-\( N \) dimensional Hermitian matrix set and a Hermitian positive semidefinite matrix set, respectively. \( \| \cdot \| \) represents the Euclidean norm of a vector. \( | \cdot | \) represents the absolute value of a complex scalar. \( x \sim \mathcal{CN}(\mathbf{u}, \Sigma) \) indicates that \( x \) is a random vector, which follows a complex Gaussian distribution with mean \( \mathbf{u} \) and covariance matrix \( \Sigma \). \( \mathbb{E}[\cdot] \) denotes the expectation operator. \( \text{Re}(\mathbf{a}) \) extracts the real part of vector \( \mathbf{a} \). \( \mathbb{R}_+ \) denotes the set of all nonnegative real numbers.

II. SYSTEM MODEL

As shown in Fig. 1, a downlink MISO CR with SWIPT is considered. The primary network coexists with the secondary network under the spectrum sharing operational paradigm. The primary network consists of a primary base station (PBS), \( N_E \) EHRs and \( N_P \) PUs. In the secondary network, the CBS transmits information to \( N_S \) secondary users (SUs) and energy to \( K \) EHRs. The primary base station (PBS) equips with \( N_P \) antennas while the CBS equips with \( N_{S,E} \) antennas. All the SUs, PUs and EHRs have one antenna. Since the radio frequency signals transmitted by the PBS and the CBS carry confidential information, EHRs may eavesdrop it. It is assumed that EHRs in each network can only wiretap and decode confidential information from the same network. In order to improve the security of both the primary network and the secondary network, the PBS and CBS adopt an AN-aided cooperation transmission strategy. Using this strategy, the CBS and PBS transmit artificial noise to jam EHRs and improve the security of these two networks. Specifically, the CBS transmit artificial noise to degrade the EHRs’ channels from these two networks. The signals received at each PU and SU are respectively denoted by \( y_{P,i} \) and \( y_{S,l} \), where \( i = 1, 2, \ldots, N_P \) and \( l = 1, 2, \ldots, N_S \). And the energy signals received at EHRs from the primary and secondary network are respectively represented by \( y_{E,n} \) and \( y_{E,k} \), where \( n = 1, 2, \ldots, N_E \) and \( k = 1, 2, \ldots, N_K \). These signals can be given as

\[
y_{P,i} = h_{P,i}^\dagger x_P + f_{P,i} x_N + n_{P,i}, \quad i = 1, 2, \ldots, N_P \tag{1a}
\]

\[
y_{S,l} = h_{S,l}^\dagger x_S + f_{S,l} x_N + n_{S,l}, \quad l = 1, 2, \ldots, N_S \tag{1b}
\]
where $h_{P,i} \in \mathbb{C}^{N_{P,i} \times 1}$ and $f_{P,i} \in \mathbb{C}^{N_{S,i} \times 1}$ are the channel vector between the PBS and the $i$th PU and that between the CBS and the $i$th PU, respectively; $g_{S,i} \in \mathbb{C}^{N_{S,i} \times 1}$ and $q_{S,i} \in \mathbb{C}^{N_{P,i} \times 1}$ denote the channel vector between the CBS and the $i$th SU and that between the PBS and the $i$th SU; $h_{E,n} \in \mathbb{C}^{N_{P,n} \times 1}$ and $f_{E,n} \in \mathbb{C}^{N_{S,n} \times 1}$ represent the channel vector between the PBS and the $n$th EHR in the primary network and that between the CBS and the $n$th EHR in the primary network; $q_{E,k} \in \mathbb{C}^{N_{P,k} \times 1}$ and $g_{E,k} \in \mathbb{C}^{N_{S,k} \times 1}$ are the channel vector between the PBS and the $k$th EHR in the secondary network and that between the CBS and the $k$th EHR in the secondary network. In (1), $n_{P,i} \sim C_{N} \left( 0, \sigma_{n_{P,i}}^{2} \right)$, $n_{S,i} \sim C_{N} \left( 0, \sigma_{n_{S,i}}^{2} \right)$, $n_{E,n} \sim C_{N} \left( 0, \sigma_{n_{E,n}}^{2} \right)$ and $n_{E,k} \sim C_{N} \left( 0, \sigma_{n_{E,k}}^{2} \right)$ respectively denote the complex Gaussian noise at the $i$th PU, $i$th SU, $n$th EHR in the primary network and the $k$th EHR in the secondary network. In (1), $x_p$ and $x_s$ are the transmit signal vector of the PBS and the CBS, given as

\begin{align*}
x_p &= w_p \tilde{x}_p + v_p \quad (2a) \\
x_s &= w_s \tilde{x}_s + v_s \quad (2b)
\end{align*}

where $v_p \sim C_{N} \left( 0, \Sigma_{p} \right)$ and $v_s \sim C_{N} \left( 0, \Sigma_{S} \right)$, where $\Sigma_{p}$ and $\Sigma_{S}$ are the AN covariance matrix to be designed. It has been shown that quantization errors can be modeled as the bounded CSI error forms. Thus, $h_{P,i}$ and $f_{P,i}$ are given as, respectively

\begin{align*}
h_{P,i} &= \tilde{h}_{P,i} + \Delta h_{P,i} \quad \text{i.e.} \quad \{1, 2, \ldots, N_{P}\} \\
g_{S,i} &= \tilde{h}_{S,i} + \Delta h_{S,i} \quad \text{i.e.} \quad \{1, 2, \ldots, N_{S}\}
\end{align*}

where $\Delta h_{P,i}$ and $\Delta h_{S,i}$ denote the estimate value of the channel vectors $h_{P,i}$ and $h_{S,i}$, respectively; $\Delta h_{P,i}$ and $\Delta h_{S,i}$ denote the uncertainty regions of $\Delta h_{P,i}$ and $\Delta h_{S,i}$; $\Delta h_{P,i}$ and $\Delta h_{S,i}$ are the corresponding channel estimation errors; $\tilde{h}_{P,i}$ and $\tilde{h}_{S,i}$ represent the radii of the uncertainty regions $\Delta h_{P,i}$ and $\Delta h_{S,i}$, respectively. Similarly, the bounded CSI error models for $q_{S,i}$, $q_{E,k}$, $h_{E,n}$, $f_{E,n}$, $q_{E,k}$ and $g_{E,k}$ can be given as, respectively

\begin{align*}
\Omega_{S,i} &= \left\{ \Delta g_{S,i} \in \mathbb{C}^{N_{S,i} \times 1} : \Delta g_{S,i} \Delta g_{S,i}^{\dagger} \leq (\tilde{g}_{S,i})^{2} \right\} \\
\Omega_{P,i} &= \left\{ \Delta f_{P,i} \in \mathbb{C}^{N_{P,i} \times 1} : \Delta f_{P,i} \Delta f_{P,i}^{\dagger} \leq (\tilde{f}_{P,i})^{2} \right\}
\end{align*}

\section{Robust AN-Aided Secure Beamforming Design}

III. ROBUST AN-AIDED SECURE BEAMFORMING DESIGN

In this section, a robust power minimization problem is formulated in CR with SWIPT based on the practical non-linear EH model while the security of both the primary network and the secondary network are guaranteed. Due to the existence of variable couple and the complex form of the harvesting energy, the formulated problem is challenging to be solved. A suboptimal solution is proposed to solve it.

\section{Nonlinear Energy Harvesting Model}

A. NONLINEAR ENERGY HARVESTING MODEL

Most of the existing works adopt a linear energy harvesting model [25]–[28], given as

\begin{equation}
P_{\text{harvesting}} = \eta P_{\text{EHR}}
\end{equation}

where $P_{\text{harvesting}}$ is the power conversed at the EHR; $\eta \in [0, 1]$ is the power conversion efficiency and $P_{\text{EHR}}$ is the received radio frequency power at the EHR. In practice, the energy harvesting circuits generally result in a nonlinear end-to-end power conversion. According to the nonlinear energy harvesting model given by [32]–[35], the energy harvesting at the EHRs denoted by $\Phi_{E,A}$ is given as

\begin{equation}
\Phi_{E,A} = \frac{(\psi_{E,A} - P_{\text{max}, E,A}) \psi_{E,A}}{1 - \psi_{E,A}}
\end{equation}
where $A$ denotes the set of EHRs in the primary network and the secondary network, namely, $A = A_1 \cup A_2$, and $A_1 = \{1, 2, \cdots, N_E\}$, $A_2 = \{1, 2, \cdots, K\}$; $P^{\text{max}}_{E,A}$ is the maximum harvested power of EHRs when the EH circuit is saturated; $a_{E,A}$ and $b_{E,A}$ are parameters that reflect the circuit specifications, such as the capacitance, the resistance, and diode turn-on voltage [32]. In (6b), $\psi_{E,A}$ is the received radio frequency power at the EHR. Let $n \in A_1$ and $k \in A_2$ denote the $n$th EHR in the primary network and the $k$th EHR in the secondary network, respectively. The received radio frequency power at the EHR can be given as

$$\Gamma_{E,n} = f^\dagger_{E,n} (w_n w_n^\dagger + \Sigma_S) f_{E,n} + h^\dagger_{E,n} (w_p w_p^\dagger + \Sigma_P) h_{E,n}, \quad (7a)$$

$$\Gamma_{E,k} = g^\dagger_{E,k} (w_n w_n^\dagger + \Sigma_S) g_{E,k} + q^\dagger_{E,k} (w_p w_p^\dagger + \Sigma_P) q_{E,k}. \quad (7b)$$

The received radio frequency power comes from two sources. One is the PBS and the other is the CBS.

**B. PROBLEM FORMULATION AND ITS SOLUTION**

To minimize the transmit power of CR with SWIT while the security of both the primary and secondary networks is guaranteed and the energy harvesting requirement of EHRs is satisfied, it is of great importance to design an efficient resource allocation scheme. In this paper, the transmitted beamforming and the AN-aided covariance matrix of both the PBS and the CBS are optimized to minimize the transmit power cost.

Let $\Upsilon_{P,i}$ and $\Upsilon_{E,n}$ denote the minimum required signal-to-interference-plus-noise ratio (SINR) at the $i$th PU and the minimum SINR at the $n$th EHRs in the primary network, respectively, where $i \in \{1, 2, \cdots, N_P\}$ and $n \in \{1, 2, \cdots, N_E\}$; $\Upsilon_{S,i}$ and $\Upsilon_{E,k}$ denote the minimum SINR at the $i$th SU and the maximum SINR at the $k$th EHRs in the secondary network, respectively, where $l \in \{1, 2, \cdots, N_S\}$ and $k \in \{1, 2, \cdots, K\}$. In order to satisfy the harvesting energy requirement of EHRs, let $\Lambda_n$ and $\Lambda_{E,k}$ represent the minimum harvesting energy of the $n$ EHR in the primary network and the $k$th EHR in the secondary network, respectively. Thus, the power minimization problem can be formulated as problem P1, given as

$$\min_{w_n, \Sigma_S, w_p, \Sigma_P} \text{Tr}\left( w_n w_n^\dagger + \Sigma_S + w_p w_p^\dagger + \Sigma_P \right) \quad (8a)$$

s.t.

$$C1: \begin{bmatrix} h^\dagger_{P,i} w_p w_p^\dagger h_{P,i} \cr f^\dagger_{P,i} (w_n w_n^\dagger + \Sigma_S) f_{P,i} + h^\dagger_{P,i} \Sigma_P h_{P,i} + \sigma^2_{P,i} \end{bmatrix} \geq \Upsilon_{P,i},$$

$$\forall \Delta h_{P,i} \in \Omega^h_{P,i}, \forall \Delta f_{P,i} \in \Omega^f_{P,i}, i \in \{1, 2, \cdots, N_P\} \quad (8b)$$

$$C2: \begin{bmatrix} h^\dagger_{E,n} w_p w_p^\dagger h_{E,n} \cr f^\dagger_{E,n} (w_n w_n^\dagger + \Sigma_S) f_{E,n} + h^\dagger_{E,n} \Sigma_P h_{E,n} + \sigma^2_{E,n} \end{bmatrix} \leq \Upsilon_{E,n},$$

$$\forall \Delta h_{E,n} \in \Omega^h_{E,n}, \forall \Delta f_{E,n} \in \Omega^f_{E,n}, n \in \{1, 2, \cdots, N_E\} \quad (8c)$$

$$C3: \begin{bmatrix} g^\dagger_{S,l} w_n w_n^\dagger g_{S,l} \cr q^\dagger_{S,l} (w_p w_p + \Sigma_P) q_{S,l} + \sigma^2_{S,k} \end{bmatrix} \geq \Upsilon_{S,l},$$

$$\forall \Delta g_{S,l} \in \Omega^g_{S,l}, \forall \Delta q_{S,l} \in \Omega^q_{S,l}, l \in \{1, 2, \cdots, N_S\} \quad (8d)$$

$$C4: \begin{bmatrix} g^\dagger_{E,k} w_n w_n^\dagger g_{E,k} \cr q^\dagger_{E,k} (w_p w_p + \Sigma_P) q_{E,k} + \sigma^2_{E,k} \end{bmatrix} \leq \Upsilon_{E,k},$$

$$\forall \Delta g_{E,k} \in \Omega^g_{E,k}, \forall \Delta q_{E,k} \in \Omega^q_{E,k}, k \in \{1, 2, \cdots, K\} \quad (8e)$$

$$C5: \Phi_{E,n} \geq \Lambda_n, \forall \Delta h_{E,n} \in \Omega^h_{E,n}, \forall \Delta f_{E,n} \in \Omega^f_{E,n} \quad (8f)$$

$$C6: \Phi_{E,k} \geq \Lambda_{E,k}, \forall \Delta g_{E,k} \in \Omega^g_{E,k}, \forall \Delta q_{E,k} \in \Omega^q_{E,k} \quad (8g)$$

In (8), the constraints C1 and C2 are given to guarantee the security of PUs in the primary network; C3 and C4 are imposed to guarantee the security of SUs in the secondary network. C5 and C6 are the energy constraints for satisfying the harvesting energy requirements of EHRs in the primary network and the secondary network, respectively. Since the energy harvesting form is nonlinear and complex, it is challenging to solve P1. Moreover, all the involved channels are identified as the realistic channel estimation model, which considers the existence of the channel estimation error. This extremely increases the difficulty to solve P1 due to infinite inequality constraints caused by the uncertain CSI regions. In order to solve P1, SD relaxation (SDR) and S-Procedure are exploited.

**Lemma 1 (S-Procedure) [36]:** It is assumed that $f_1(z) = z^\dagger A_i z + 2 \text{Re} \left[ b_i^\dagger z \right] + c_i$, $i \in \{1, 2\}$, where $z \in \mathbb{C}^{N \times 1}$, $A_i \in \mathbb{C}^{N \times N}$, $b_i \in \mathbb{C}^{N \times 1}$ and $c_i \in \mathbb{R}$. Then, the expression $f_1(z) \leq 0 \Rightarrow f_2(z) \leq 0$ holds if and only if there exists a $\alpha \geq 0$ such that

$$\alpha \left[ A_1 b_1\, b_1^\dagger c_1 \right] - \left[ A_2 b_2\, b_2^\dagger c_2 \right] \succeq 0 \quad (9)$$

if there exists a vector $\tilde{z}$ such that $f_1(\tilde{z}) < 0$.

Let $W_P = w_p w_p^\dagger$, $W_S = w_n w_n^\dagger$, $O_{P,i} = [I \, \tilde{h}_{P,i}]$ and $X_{P,i} = [I \, \tilde{h}_{P,i}]$. Using Lemma 1, the constrain C1 can be written as linear forms, given as

$$\begin{bmatrix} 0 \cr -\tau_{P,i} - \sigma_{P,i} (\tilde{\rho}_{P,i})^2 \cr \sigma_{P,i}^2 \end{bmatrix} \succeq 0 \quad (10a)$$
where $\sigma_{P,i} \geq 0$, $\alpha_{P,i} \geq 0$ and $\tau_{P,i}$ are slack variables. Similarly, Let $O_{E,n} = [I \bar{h}_{E,n}]$ and $X_{E,n} = [I \bar{r}_{E,n}]$. The constraint $C2$ can be rewritten as

$$
\begin{bmatrix}
\alpha_{E,n} I & 0 \\
0 & \tau_{E,n} - \sigma_{E,n}^2 (\beta_{E}^f) \\
-\sigma_{E,n}^2 (\omega_{E,n})^2 & 0 \\
\end{bmatrix}
+ X_{E,n}^H (W_S + \Sigma_S) X_{E,n} \geq 0
$$

(10a)

$$
\begin{bmatrix}
\alpha_{E,n}^2 & 0 \\
0 & \tau_{E,n} - \sigma_{E,n}^2 (\omega_{E,n})^2 \\
\end{bmatrix}
+ X_{E,n}^H (W_S + \Sigma_S) X_{E,n} \geq 0
$$

(11b)

where $\sigma_{E,n} \geq 0$, $\alpha_{E,n} \geq 0$ and $\tau_{E,n}$ are slack variables. Let $O_{S,i} = [I \bar{h}_{S,i}]$, $X_{S,i} = [I \bar{r}_{S,i}]$, $Y_{S,i} = [W_S - \gamma_{S,i} \Sigma_S]$, $O_{E,k} = [I \bar{h}_{E,k}]$, $X_{E,k} = [I \bar{r}_{E,k}]$, and $Y_{E,k} = [W_S - \gamma_{E,k} \Sigma_S]$. The constraints $C3$ and $C4$ are expressed as linear forms, given as

$$
\begin{bmatrix}
\omega_{S,i} & 0 \\
0 & \tau_{S,i} - \sigma_{S,i}^2 (\omega_{S,i})^2 \\
\end{bmatrix}
+ O_{S,i}^H Y_{S,i} O_{S,i} \geq 0
$$

(12a)

$$
\begin{bmatrix}
\alpha_{S,i} & 0 \\
0 & \tau_{S,i} - \sigma_{S,i}^2 (\omega_{S,i})^2 \\
\end{bmatrix}
+ X_{S,i}^H (W_P + \Sigma_P) X_{S,i} \geq 0
$$

(12b)

$$
\begin{bmatrix}
\omega_{E,k} & 0 \\
0 & \tau_{E,k} - \sigma_{E,k}^2 (\omega_{E,k})^2 \\
\end{bmatrix}
+ O_{E,k}^H Y_{E,k} O_{E,k} \geq 0
$$

(12c)

where $\sigma_{S,i} \geq 0$, $\alpha_{S,i} \geq 0$, $\sigma_{E,k} \geq 0$, $\alpha_{E,k} \geq 0$, $\tau_{S,i}$ and $\tau_{E,k}$ are slack variables.

Similarly, using Lemma 1, the constraints $C5$ and $C6$ can be expressed as

$$
\begin{bmatrix}
\beta_{E,n} & 0 \\
0 & -\gamma_{E,n} - \alpha_{E,n} (\omega_{E,n})^2 \\
\end{bmatrix}
+ X_{E,n}^H (W_S + \Sigma_S) X_{E,n} \geq 0
$$

(13a)

$$
\begin{bmatrix}
\beta_{E,k} & 0 \\
0 & -\gamma_{E,k} - \alpha_{E,k} (\omega_{E,k})^2 \\
\end{bmatrix}
+ X_{E,k}^H (W_S + \Sigma_S) X_{E,k} \geq 0
$$

(13b)

$$
\begin{bmatrix}
\omega_{E,n} & 0 \\
0 & \gamma_{E,n} - \beta_{E,n} (\omega_{E,n})^2 \\
\end{bmatrix}
+ X_{E,n}^H (W_S + \Sigma_S) X_{E,n} \geq 0
$$

(13c)

where $\omega_{E,n} \geq 0$, $\beta_{E,n} \geq 0$, $\gamma_{E,n} \geq 0$, $\beta_{E,k} \geq 0$, $\gamma_{E,k} \geq 0$, and $\gamma_{E,n}$ and $\gamma_{E,k}$ are slack variables. Using the SDR method [36], problem $P_1$ can be relaxed as problem $P_2$, given as

$$
\begin{bmatrix}
\beta_{E,k} & 0 \\
0 & -\gamma_{E,k} - \beta_{E,k} (\omega_{E,k})^2 \\
\end{bmatrix}
+ X_{E,k}^H (W_P + \Sigma_P) X_{E,k} \geq 0
$$

(13d)

where $\omega_{E,n} \geq 0$, $\beta_{E,n} \geq 0$, $\omega_{E,k} \geq 0$, $\beta_{E,k} \geq 0$, $\gamma_{E,n}$ and $\gamma_{E,k}$ are slack variables. Using the SDR method and the rank-one solution cannot be proved, the optimal solution may not be obtained. If the solutions for $W_S$ and $W_P$ are rank-one, the optimal robust beamforming for $P_1$ can be obtained by using the eigenvalue decomposition. If the solutions for $W_S$ and $W_P$ are not rank-one, the well-known Gaussian randomization procedure can be applied to obtain the suboptimal robust beamforming vector [38].

**IV. SIMULATION RESULTS**

In this section, simulation results are given to compare the performance achieved under the non-linear EH model with that obtained under the linear EH model. The number of PUs and EHRs in the primary network are set as 2; The number of SU and EHRs in the primary network are 1. The number of antennas of the PBS and the CBS is set as 20 and 5, respectively. The parameters of the non-linear EH model are set based on the work in [34], namely $d_{E,A}^{max} = 1500$, $d_{E,A}^{max} = 0.0022$, $P_{E,A}^{max} = 24$ mW. The corresponding energy conversion efficiency of the compared linear energy harvesting model is 0.5. The channel gains are set as $\tilde{h}_{P,i} \sim CN(0, 2I)$, $\tilde{r}_{E,n} \sim CN(0, 1I)$, $\tilde{g}_{S,i} \sim CN(0, 1I)$, $\tilde{h}_{E,n} \sim CN(0, 2I)$, $\tilde{r}_{E,k} \sim CN(0, 0, 1I)$, $\tilde{g}_{E,k} \sim CN(0, 0, 1I)$ and $\tilde{g}_{E,k} \sim CN(0, 0, 1I)$. The thermal noise power is $-120$ dBm. The SINR are set as $\gamma_{E,n} = 20$ dB, $\gamma_{E,n} = 0$ dB, $\gamma_{S,i} = 10$ dB, and $\gamma_{E,k} = 0$ dB. The energy harvesting requirements are $\Lambda_{E,k} = 0$ dBm and $\Lambda_{E,n} = 0$ dBm. The CSI errors are set as $\sigma_{E,A}^{max} = 0.01$, $\sigma_{E,A}^{max} = 0.01$, $\gamma_{E,i} = 0.01$, $\gamma_{E,i} = 0.01$, $\gamma_{E,k} = 0.01$, $\gamma_{E,k} = 0.01$, $\gamma_{E,k} = 0.01$, and $\gamma_{E,k} = 0.01$.

Figure 2 shows the empirical cumulative distribution function (CDF) of the minimum transmission power achieved under the non-linear EH model and the linear EH model with the perfect CSI and imperfect CSI. The perfect CSI means that $\gamma_{E,i} = 0$. It is seen that the minimum transmission power achieved under the non-linear EH model is lower than that achieved under the linear EH model. The reason is that the resource allocation proposed based on the nonlinear EH model can better match the practical EH circuit. This phenomena has also been demonstrated in [32]–[35]. It is also seen that the accuracy of the CSI has an effect on the
FIGURE 2. The empirical cumulative distribution function of the minimum transmission power achieved under the non-linear EH model and the linear EH model with the perfect CSI and imperfect CSI.

FIGURE 3. The minimum transmission power versus the minimum SINR of PUs achieved under the non-linear EH model and the linear EH model with different numbers of antennas of the CBS.

Figure 3 shows the minimum transmission power versus the minimum SINR of PUs achieved under the non-linear EH model and the linear EH model with different numbers of antennas of the CBS. The number of antennas of the CBS is set as 5 or 10. The number of EHRs in the primary network is 2. It is seen that the minimum transmission power increases with the minimum SINR requirement of PUs. It is also seen that the performance achieved under the non-linear EH model is better than that achieved under the linear EH model. Moreover, as shown in Fig. 3, the minimum transmission power decreases with the increase of the antennas of the CBS, irrespective of the non-linear EH model or the linear EH model. The reason is that the increase of the number of antennas improves the degrees of freedom. For example, with more transmit antennas equipped at the CBS, the AN transmitted by the CBS can be more efficiently steered in the direction of EHRs in the primary network which can improve the secrecy rate of the primary users and the harvesting energy of EHRs.

FIGURE 4. The minimum transmission power versus the number of EHRs in the primary network achieved under the non-linear EH model and the linear EH model with or without cooperation between the primary network and the secondary network.

Figure 4 shows the minimum transmission power versus the number of EHRs in the primary network achieved under the non-linear EH model and the linear EH model with or without cooperation between the primary network and the secondary network. The minimum SINR of PUs is set as 20 dB. It is seen that the minimum transmission power increases with the number of EHRs in the primary network irrespective of the non-linear EH model or the linear EH model. The reason is that the secrecy rate decreases with the increase of the number of EHRs in the primary network. In order to guarantee the security of PUs, the transmit power is required to be increased. It is also observed that our proposed cooperation scheme can obtain a performance gain compared with that scheme that there does not exist cooperation between the primary network and the secondary network. It can be easily explained by the fact that the cooperation by using AN can disturb EHRs to intercept the confidential information for PUs and SUs.

In order to verify the performance gain obtained by using our proposed cooperation scheme, Fig. 5 is given to show the minimum transmission power versus the number of antennas...
of the CBS achieved under the non-linear EH model and the linear EH model with or without cooperation between the primary network and the secondary network. The number of EHRS in the primary network is set to be 3. It is also seen that our proposed cooperation scheme can obtain a performance gain. As also shown in Fig. 5, the minimum transmission power decreases with the increase of antennas of the CBS.

V. CONCLUSION

A power minimization problem was formulated in a MISO CR network based on a practical non-linear EH model. To guarantee the security of both the primary network and the secondary network, a cooperative jamming scheme was proposed. A suboptimal robust AN-aided beamforming scheme was designed under the bounded CSI error model. It was shown that the non-linear EH model may provide better performance compared with the linear EH model. It was also shown that our proposed cooperation scheme can obtain a performance gain compare with the scheme without cooperation between the primary network and the secondary network.

In this paper, a single cast link was considered. In order to improve spectrum efficiency, a multi-cast scenario or a non-orthogonal multiple access CR will be focused. We will study robust AN-aided beamforming schemes for these networks to achieve secure communications and obtain a high spectrum efficiency.

REFERENCES


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VOLUME 5, 2017