2018 IEEE Wireless Communications and Networking Conference (WCNC)

Destination-assisted Jamming for Physical-Layer Security in SWIPT Cognitive Radio Systems

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***Abstract*—In this paper, we investigate the security for cognitive radio networks with simultaneous wireless information and power transfer (SWIPT). In such a system, an energy-limited secondary user (SU) helps relay the traffic from a primary user (PU) to the primary receiver (PR) and assists PU secure communication using beamforming technology, in return to serve its own secondary receiver in the same spectrum. In order to further enhance the security of PU traffic performance and increase the energy harvested by SU, we propose a destination-assisted scheme in which the PR transmits jamming signal to confuse the eavesdropper, while jamming signal can also be used to power SU. The beamforming vectors and power split ratio are jointly designed to maximize the secrecy rate of PU while satisfying the rate demand of SU. It boils down to a challenging non-convex problem. We resolve this issue by a general two-stage procedure. First, by fixing the power split ratio, we obtain the optimal beamforming vectors by applying the semi-definite relaxation (SDR) technique and the Charnes Cooper transformation. Then, the problem is solved by a one-dimension search to obtain the optimal power split ratio. Extensive simulations are provided and the results demonstrate that our proposed scheme has good performance.**

***Index Terms*—Physical layer security, wireless information and power transfer, cognitive radio networks, beamforming design, power splitting.**

I. Introduction

The escalating high data rate requirements have resulted in severe spectrum scarcity problem. Cognitive radio (CR) has emerged as one of the most effective solutions for improving the spectrum efficiency in wireless networks [1]. Among proposals for the implementation of CR, a spectrum-leasing framework whereby the primary users (PUs) lease spectral resources to secondary users (SUs) in exchange for cooperation has been proposed in [2]. In cooperative CR networks, SUs assist to relay the messages of PUs for accessing the same spectrum to send their own information to secondary receivers (SRs), which is a win-win strategy. That is particularly preferred by primary system when the primary system itself can not meet the quality of service (QoS) of the PU. One problem is that even when the SU has good channel quality to help relay the PU but is energy limited, cooperation is still unable to complete. This is a very common situation when the SU is a low-power relay node. Therefore, solving the problem of energy scarcity is very significant, especially for the CR network with energy-limited devices [3]. Simultaneous wireless information and power transfer (SWIPT), which enables the concurrent transmission of information and energy, has attracted much attention as a promising technology to solve the energy scarcity problem [4]. In [5], authors have proved that energy-limited secondary user (SU) with energy harvesting can be strongly stimulated in CR networks.

On the other hand, due to the broadcast nature of wireless communications, security is always a major concern in wireless networks. PU also has the requirements of secure communication in CR networks, by reason of the existence of eavesdroppers causing the legitimate user information disclosure. Physical layer security as a promising way has been proposed to prevent eavesdropping [6]. Cooperation techniques for physical layer security, e.g., cooperative forwarding, friendly jamming, and beamforming [7], [8], have been presented to improve the secrecy rate. [9] and [10] have considered the physical layer security combined SWIPT in CR networks. In [9], the authors focus on designing artificial noise (AN)-aided beamforming for secure SU transmission. They assume SU powered by cognitive base station (CBS) can share the same spectrum with PU as long as the interference imposed on PU receiver is tolerable. The scene of [10] is similar to [9], the difference is that the SU harvests energy from PU but not CBS. Notice that in [9], [10], the PU allows the SU to access the licensed spectrum without requiring any benefit. Such altruistic behavior is arguably unrealistic.

Motivated by the discussion above, we consider such a scenario that PU can not directly transfer information to the primary receiver (PR) due to the bad channel condition, even worse, the eavesdropper around the PR can overhear the transmission. If spectrum access is allowed by PU, the energy-limited SU can utilize the energy harvested from PU to help relay the traffic from PU and assist PU secure communication using beamforming technology, on the condition that the QoS demand of SU should be satisfied. Different from [9] and [10], we introduce the cooperation mechanism between SU and PU. In addition, for the purpose of enhancing the security of PU traffic performance and increasing the energy that harvested by SU, we propose a destination-assisted jamming transfer scheme, where PR transmits jamming signal to confuse the eavesdropper. The jamming signal can not only interfere with eavesdropper, but also can supply energy for SU. In this paper, the beamforming vectors and power split ratio are jointly designed to maximize the secrecy rate of PU while satisfying

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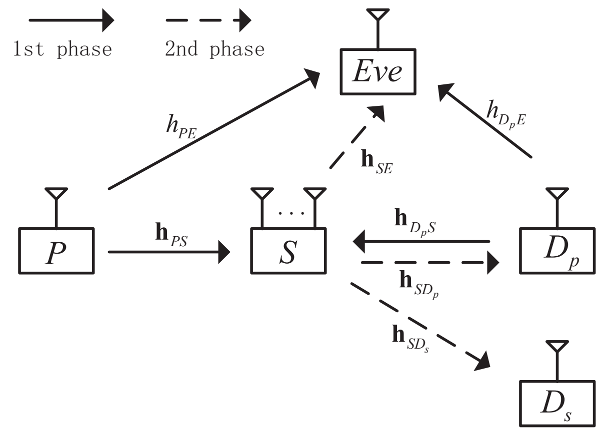

Fig. 1. Secrecy SWIPT in cognitive radio system with destination-assisted.

the rate demand of SU. Since the problem is non-convex, a general two-stage procedure is deemed. First, we obtain the optimal beamforming vectors with fixed power split ratio. Then, the optimal power split ratio is obtained by a one-dimension search.

The rest of this paper is organized as follows. In Section II, system model and problem formulation are introduced. Section III presents the optimal solution for the formulated problem. The simulation results are presented and discussed in Section IV. Finally, Section V concludes the paper.

II. System model and problem formulation

We consider a destination-assisted secrecy cognitive radio system with SWIPT, which consists of a PU, a PR, an energy-limited SU, a SR and an eavesdropper, denoted by P, D_p, S, D_s and Eve, respectively. S assists to forward the traffic from P to D_p with decode-and-forward (DF) protocol, simultaneously serving its own D_s in the same spectrum, as illustrated in Fig.1. The S is equipped with M antennas, while other nodes have a single antenna. We assume that S is energy-limited and powered by both information flow from P and jamming flow which is used to confuse the Eve from D_p in the first phase. In addition, we assume all channel state information (CSI), including that of the Eve, is available [11], [12]. The information of eavesdroppers' channels can be obtained when the eavesdroppers are active in the network, e.g. eavesdroppers are users of the network but do not have authorization to acquire the current services [13], e.g., pay-TV broadcast services. Assume that entire communication time slot, which consists of two equal phases, is normalized to be 1.

In the first phase, P transmits information signal x_1. Meanwhile, D_p transmits jamming signal x_D, using to interfere with the eavesdropper ($\mathrm{E}[|x_1|^2] = \mathrm{E}[|x_D|^2] = 1$), where $\mathrm{E}[\cdot]$ denotes statistical expectation.

The signal received at S is then expressed as

$$\mathbf{y}_S = \sqrt{P_P}\mathbf{h}_{PS}x_1 + \sqrt{P_D}\mathbf{h}_{D_pS}x_D + \mathbf{n}_S, \tag{1}$$

where $\mathbf{h}_{PS}$ and $\mathbf{h}_{D_pS}$ are $M \times 1$ channel vectors from P to S, D_p to S, respectively; P_P and P_D are the transmission power of P and D_p, respectively; $\mathbf{n}_S \sim \mathcal{CN}\left(0, \sigma_S^2\mathbf{I}_M\right)$ is the received noise vector at S.

Based on the power split (PS) scheme, the received signal at S is split into two streams, one for information-decoding (ID) and one for energy-harvesting (EH), with the relative ratio of ρ and $1-\rho$, respectively.

The signal for EH and the harvested energy at S are then expressed as

$$\mathbf{y}_S^{EH} = \sqrt{1-\rho}\left(\sqrt{P_P}\mathbf{h}_{PS}x_1 + \sqrt{P_D}\mathbf{h}_{D_pS}x_D + \mathbf{n}_S\right) \tag{2}$$

and

$$P_S = (1-\rho)\,\eta\left(P_P\|\mathbf{h}_{PS}\|^2 + P_D\left\|\mathbf{h}_{D_pS}\right\|^2\right), \tag{3}$$

where $0 \le \eta \le 1$ is the energy conversion efficiency. The noise power is ignored compared with the signal power.

The signal for ID received at S is then expressed as

$$\mathbf{y}_S^{ID} = \sqrt{\rho}\left(\sqrt{P_P}\mathbf{h}_{PS}x_1 + \sqrt{P_D}\mathbf{h}_{D_pS}x_D + \mathbf{n}_S\right) + \mathbf{n_c}, \tag{4}$$

where $\mathbf{n_c} \sim \mathcal{CN}\left(0, \sigma_c^2\mathbf{I}_M\right)$ denotes the $M \times 1$ circuit noise vector caused by the signal frequency conversion from radio frequency (RF) to baseband. Applying the receiver vector $\mathbf{w}_S$ ($\|\mathbf{w}_S\|^2 = 1$), the estimated signal at S then can be given by

$$y_{S1} = \mathbf{w}_S^H\left[\sqrt{\rho}\left(\sqrt{P_P}\mathbf{h}_{PS}x_1 + \sqrt{P_D}\mathbf{h}_{D_pS}x_D + \mathbf{n}_S\right) + \mathbf{n_c}\right]. \tag{5}$$

The received signal-to-interference-plus-noise ratio (SINR) at S is represented as

$$\gamma_S = \frac{\rho P_P\left|\mathbf{w}_S^H\mathbf{h}_{PS}\right|^2}{\rho P_D\left|\mathbf{w}_S^H\mathbf{h}_{D_pS}\right|^2 + \rho\sigma_S^2 + \sigma_c^2}. \tag{6}$$

In order to avoid the impact of x_D on the S, we propose a ZF-based beamforming scheme. Assume $\mathbf{w}_S$ lies in the null space of $\mathbf{h}_{D_pS}$, i.e. $\mathbf{w}_S^H\mathbf{h}_{D_pS} = 0$. Then, optimization problem of maximizing the SINR in (6), can be formulated as

$$\begin{aligned} &\max_{\mathbf{w}_S} \left|\mathbf{w}_S^H\mathbf{h}_{PS}\right|^2 \\ &s.t.\ \mathbf{w}_S^H\mathbf{h}_{D_pS} = 0, \\ &\quad\ \ \mathbf{w}_S^H\mathbf{w}_S = 1. \end{aligned} \tag{7}$$

The problem in (7) is referred to as the null-steering beamformer in the array signal processing literature, and its optimal solution is given by [11]

$$\mathbf{w}_S = \frac{\left(\mathbf{I}_M - \mathbf{S}_{D_pS}\right)\mathbf{h}_{PS}}{\left\|\left(\mathbf{I}_M - \mathbf{S}_{D_pS}\right)\mathbf{h}_{PS}\right\|}, \tag{8}$$

where $\mathbf{S}_{D_pS} = \mathbf{h}_{D_pS}\left(\mathbf{h}_{D_pS}^H\mathbf{h}_{D_pS}\right)^{-1}\mathbf{h}_{D_pS}^H$.

The signal received at Eve is then expressed as

$$y_{e_1} = \sqrt{P_P}h_{PE}x_1 + \sqrt{P_D}h_{D_pE}x_D + n_{e_1}, \tag{9}$$

where h_{PE} and h_{D_pE} are channel coefficients from P to Eve, D_p to Eve, respectively; $n_{e_1} \sim \mathcal{CN}\left(0, \sigma_{e_1}^2\right)$ is additive Gaussian white noise (AWGN) at Eve.

The SINR at Eve is expressed as

$$\gamma_{E_1} = \frac{P_P |h_{PE}|^2}{P_D \left|h_{D_pE}\right|^2 + \sigma_{e_1}^2}. \tag{10}$$

In the second phase, S using DF protocol acts as a relay to transmit the signal x_1 that from P to D_p and the signal x_2 ($\mathrm{E}[|x_2|^2] = 1$) that from S to D_s. The transmit signal at S is

$$\mathbf{x}_S = \sqrt{P_S}\mathbf{w}_1 x_1 + \sqrt{P_S}\mathbf{w}_2 x_2, \tag{11}$$

where $\mathbf{w}_1 \in \mathbb{C}^{M\times 1}$ and $\mathbf{w}_2 \in \mathbb{C}^{M\times 1}$ denote the beamforming vectors for D_p and D_s, respectively.

The received signals at D_p, D_s and Eve are respectively expressed as

$$y_{D_p} = \sqrt{P_S}\mathbf{h}_{SD_p}^H \mathbf{w}_1 x_1 + \sqrt{P_S}\mathbf{h}_{SD_p}^H \mathbf{w}_2 x_2 + n_{D_p}, \tag{12}$$

$$y_{D_s} = \sqrt{P_S}\mathbf{h}_{SD_s}^H \mathbf{w}_1 x_1 + \sqrt{P_S}\mathbf{h}_{SD_s}^H \mathbf{w}_2 x_2 + n_{D_s}, \tag{13}$$

$$y_{E_2} = \sqrt{P_S}\mathbf{h}_{SE}^H \mathbf{w}_1 x_1 + \sqrt{P_S}\mathbf{h}_{SE}^H \mathbf{w}_2 x_2 + n_{E_2}, \tag{14}$$

where $\mathbf{h}_{SD_p}$, $\mathbf{h}_{SD_s}$ and $\mathbf{h}_{SE}$ are $M \times 1$ channel vectors from S to D_p, S to D_s and S to Eve, respectively; $n_{D_p} \sim \mathcal{CN}\left(0, \sigma_{D_p}^2\right)$, $n_{D_s} \sim \mathcal{CN}\left(0, \sigma_{D_s}^2\right)$, $n_{E_2} \sim \mathcal{CN}\left(0, \sigma_{E_2}^2\right)$ are AWGNs at D_p, D_s and Eve, respectively.

The received SINRs at D_p, D_s and Eve are respectively given by

$$\gamma_{D_p} = \frac{(1-\rho)\, a \left|\mathbf{h}_{SD_p}^H \mathbf{w}_1\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SD_p}^H \mathbf{w}_2\right|^2 + \sigma_{D_p}^2}, \tag{15}$$

$$\gamma_{D_s} = \frac{(1-\rho)\, a \left|\mathbf{h}_{SD_s}^H \mathbf{w}_2\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SD_s}^H \mathbf{w}_1\right|^2 + \sigma_{D_s}^2}, \tag{16}$$

$$\gamma_{E_2} = \frac{(1-\rho)\, a \left|\mathbf{h}_{SE}^H \mathbf{w}_1\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SE}^H \mathbf{w}_2\right|^2 + \sigma_{E_2}^2}, \tag{17}$$

where $a = \eta \left(P_P \|\mathbf{h}_{PS}\|^2 + P_D \left\|\mathbf{h}_{D_pS}\right\|^2\right)$.

Therefore, the achievable secrecy rate at D_p can be expressed as

$$\begin{aligned} R_p = \frac{1}{2}\min\left[\log_2\left(1+\gamma_S\right), \log_2\left(1+\gamma_{D_p}\right)\right] \\ - \frac{1}{2}\log_2\left(1+\gamma_{E_1}+\gamma_{E_2}\right). \end{aligned} \tag{18}$$

The achievable rate at S can be expressed as

$$R_s = \frac{1}{2}\log_2\left(1+\gamma_{D_s}\right). \tag{19}$$

In order to stimulate the SU to help PU relay the traffic and aid PU secure communication, the minimum QoS demand of SU should be guaranteed [14], [15]. Therefore, we focus on the joint design of power split ratio ρ and beamforming vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ to maximize the achieved secrecy rate of D_p, under the minimal rate demand of D_s and power constraint of S in this paper. The optimization problem is formulated as ($\mathcal{P}1$)

$$\mathcal{P}1: \max_{\mathbf{w}_1,\mathbf{w}_2,0\le\rho\le1} \; R_p \tag{20a}$$

$$s.t. \quad R_s \ge R_{\min}, \tag{20b}$$

$$\|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 \le 1, \tag{20c}$$

where $R_{\min}$ is the minimal rate demand at node D_s. Constraint (20b) is to guarantee the minimal rate constrain of D_s and (20c) is the transmission power constraint of S.

III. Optimisation solution

Obviously, problem ($\mathcal{P}1$) is a non-convex problem. In this section, a general two-stage procedure is proposed to solve problem ($\mathcal{P}1$). With fixed ρ , optimal $\mathbf{w}_1$ and $\mathbf{w}_2$ are obtained, and then the optimal ρ is found via bisection. In what follows, we firstly focus on the design of optimal $\mathbf{w}_1$ and $\mathbf{w}_2$ with fixed ρ.

When the relay adopts DF protocol, the rate of the relay link is limited by the SINR of the inferior phase. Therefore, the system rate will be optimal when $\gamma_S = \gamma_{D_p}$ [16]. In addition, from the expression (6), we can note that γ_S is only related to variable ρ. Therefore, the problem ($\mathcal{P}1$) can be equivalently written as ($\mathcal{P}2$)

$\mathcal{P}2$:

$$\max_{\mathbf{w}_1,\mathbf{w}_2} \; \log_2\left(1+\gamma_{D_p}\right) - \log_2\left(1+\gamma_{E_1}+\gamma_{E_2}\right) \tag{21a}$$

$$s.t. \quad \frac{1}{2}\log_2\left(1+\gamma_{D_s}\right) \ge R_{\min}, \tag{21b}$$

$$\|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 \le 1. \tag{21c}$$

When the problem ($\mathcal{P}2$) is solved, we can use the equation relationship $\gamma_S = \gamma_{D_p}$, through the bisection to find the optimal value of ρ.

Next, we propose a SDR-based algorithm to solve problem ($\mathcal{P}2$) by reformulating it into two sub-problems. First, from the expression (10), we can note that γ_{E_1} is a constant, so we mainly focus on γ_{E_2}. Similar to [17], it can be shown that there always exists a SINR constraint γ_e at Eve such that the following problem ($\mathcal{P}3$) has the same optimal solution to ($\mathcal{P}2$).

$\mathcal{P}3$:

$$\max_{\mathbf{w}_1,\mathbf{w}_2} \; \frac{(1-\rho)\, a \left|\mathbf{h}_{SD_p}^H \mathbf{w}_1\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SD_p}^H \mathbf{w}_2\right|^2 + \sigma_{D_p}^2} \tag{22a}$$

$$s.t. \quad \frac{(1-\rho)\, a \left|\mathbf{h}_{SE}^H \mathbf{w}_1\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SE}^H \mathbf{w}_2\right|^2 + \sigma_{E_2}^2} \le \gamma_e, \tag{22b}$$

$$\frac{(1-\rho)\, a \left|\mathbf{h}_{SD_s}^H \mathbf{w}_2\right|^2}{(1-\rho)\, a \left|\mathbf{h}_{SD_s}^H \mathbf{w}_1\right|^2 + \sigma_{D_s}^2} \ge \gamma_{\min}, \tag{22c}$$

$$\|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 \le 1, \tag{22d}$$

where $\gamma_{\min} = 2^{2R_{\min}} - 1$ is the minimal SINR requirement at D_s.

Let $g_1(\gamma_e)$ denote the optimal value of problem ($\mathcal{P}3$) with a given $\gamma_e > 0$. Then, it can be also shown that the optimal value of ($\mathcal{P}2$) is the same as that of the following problem

$$\mathcal{P}3.1 : \operatorname*{Max}_{\gamma_e>0}\ \log_2\left(\frac{1+g_1(\gamma_e)}{1+\gamma_{E_1}+\gamma_e}\right). \tag{23}$$

Let γ_e^* denote the optimal solution to problem ($\mathcal{P}3.1$). From the above results, with $\gamma_e = \gamma_e^*$, ($\mathcal{P}2$) and ($\mathcal{P}3$) have the same optimal solution. Therefore, ($\mathcal{P}2$) can be solved in the following two steps: the optimal γ_e for ($\mathcal{P}3.1$) is obtained by one dimension search over $\gamma_e > 0$, while given any γ_e, $g_1(\gamma_e)$ is obtained by solving ($\mathcal{P}3$). Hence, in the rest of this section, we focus on solving ($\mathcal{P}3$).

Note that ($\mathcal{P}3$) is non-convex. Define $\mathbf{H}_{SD_p} = \mathbf{h}_{SD_p}\mathbf{h}_{SD_p}^H$, $\mathbf{H}_{SE} = \mathbf{h}_{SE}\mathbf{h}_{SE}^H$, $\mathbf{W}_1 = \mathbf{w}_1\mathbf{w}_1^H$ and $\mathbf{W}_2 = \mathbf{w}_2\mathbf{w}_2^H$, and by ignoring the rank-one constraint on $\mathbf{W}_1$ and $\mathbf{W}_2$, the SDR of problem ($\mathcal{P}3$) can be relaxed as

$\mathcal{P}3 - SDR:$

$$\max_{\mathbf{W}_1,\mathbf{W}_2}\ \frac{(1-\rho)\,a\ \mathrm{Tr}\left(\mathbf{H}_{SD_p}\mathbf{W}_1\right)}{(1-\rho)\,a\mathrm{Tr}\left(\mathbf{H}_{SD_p}\mathbf{W}_2\right)+\sigma_{D_p}^2} \tag{24a}$$

$$s.t.\ \ (1-\rho)\,a\left(\mathrm{Tr}\left(\mathbf{H}_{SE}\mathbf{W}_1\right)-\gamma_e\mathrm{Tr}\left(\mathbf{H}_{SE}\mathbf{W}_2\right)\right)\le\gamma_e\sigma_{E_2}^2, \tag{24b}$$

$$(1-\rho)\,a\left(\mathrm{Tr}\left(\mathbf{H}_{SD_s}\mathbf{W}_2\right)-\gamma_{\min}\mathrm{Tr}\left(\mathbf{H}_{SD_s}\mathbf{W}_1\right)\right)\ge\gamma_{\min}\sigma_{D_s}^2, \tag{24c}$$

$$\mathrm{Tr}\left(\mathbf{W}_1\right)+\ \mathrm{Tr}\left(\mathbf{W}_2\right)\le 1. \tag{24d}$$

If the optimal solution to problem ($\mathcal{P}3-SDR$), denoted by $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$, satisfies $Rank\left(\mathbf{W}_1^*\right)=1$ and $Rank\left(\mathbf{W}_2^*\right)=1$, the optimal information beams $\mathbf{w}_1^*$ and $\mathbf{w}_2^*$ for problem ($\mathcal{P}3$) can be obtained from the eigenvalue decomposition (EVD) of $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$; otherwise, if $Rank\left(\mathbf{W}_1^*\right) > 1$ or $Rank\left(\mathbf{W}_2^*\right) > 1$, then the optimal value of problem ($\mathcal{P}3-SDR$) only serves as an upper bound on that of problem ($\mathcal{P}3$). In the following, we will check $Rank\left(\mathbf{W}_1^*\right)=1$ and $Rank\left(\mathbf{W}_2^*\right)=1$ always hold for ($\mathcal{P}3$).

Problem ($\mathcal{P}3-SDR$) is still non-convex since its objective function is non-concave over $\mathbf{W}_1$ and $\mathbf{W}_2$. Fortunately, we can apply the Charnes-Cooper transformation [18] to reformulate ($\mathcal{P}3-SDR$) as an equivalent convex problem. Define $\bar{\mathbf{W}}_1 = t\mathbf{W}_1$, $\bar{\mathbf{W}}_2 = t\mathbf{W}_2$ ($t>0$), then we rewrite the problem ($\mathcal{P}3-SDR$) as ($\mathcal{P}3.2$)

$$\mathcal{P}3.2:\quad \max_{\bar{\mathbf{W}}_1,\bar{\mathbf{W}}_2,t>0}\ (1-\rho)\,a\ \mathrm{Tr}\left(\mathbf{H}_{SD_p}\bar{\mathbf{W}}_1\right) \tag{25a}$$

$$s.t.\quad (1-\rho)\,a\mathrm{Tr}\left(\mathbf{H}_{SD_p}\bar{\mathbf{W}}_2\right)+t\sigma_{D_p}^2=1, \tag{25b}$$

$$(1-\rho)\,a\left(\mathrm{Tr}\left(\mathbf{H}_{SE}\bar{\mathbf{W}}_1\right)-\gamma_e\mathrm{Tr}\left(\mathbf{H}_{SE}\bar{\mathbf{W}}_2\right)\right)\le t\gamma_e\sigma_{E_2}^2, \tag{25c}$$

$$(1-\rho)\,a\mathrm{Tr}\left(\mathbf{H}_{SD_s}\bar{\mathbf{W}}_2\right)-\gamma_{\min}(1-\rho)\,a\mathrm{Tr}\left(\mathbf{H}_{SD_s}\bar{\mathbf{W}}_1\right)\ge t\gamma_{\min}\sigma_{D_s}^2, \tag{25d}$$

$$\mathrm{Tr}\left(\bar{\mathbf{W}}_1\right)+\ \mathrm{Tr}\left(\bar{\mathbf{W}}_2\right)\le t, \tag{25e}$$

which is convex SDP and can be efficiently solved by convex optimization solvers, e.g., CVX.

Remark 1: It is worth being aware of that problem ($\mathcal{P}3.2$) belongs to the so-called "separable SDP" [19]. According to the [17, Theorem 3.2], there exists an optimal solution $\left(\bar{\mathbf{W}}_1^*, \bar{\mathbf{W}}_2^*, \rho^*\right)$ to problem ($\mathcal{P}3.2$) such that $Rank^2\left(\bar{\mathbf{W}}_1^*\right)+Rank^2\left(\bar{\mathbf{W}}_2^*\right)\le 4$, where 4 denotes the number of constraints. Considering the non-trivial case where $\bar{\mathbf{W}}_1^*\ne 0$, $\bar{\mathbf{W}}_2^*\ne 0$, we have $Rank\left(\bar{\mathbf{W}}_1^*\right)=1$ and $Rank\left(\bar{\mathbf{W}}_2^*\right)=1$. So the SDR problem is tight and then we can obtain the optimal information beams $\mathbf{w}_1^*$ and $\mathbf{w}_2^*$ for problem ($\mathcal{P}3$).

So far, the optimal solution to problem ($\mathcal{P}3$) is derived with fixed γ_e. In the sequel, we will find the optimal γ_e^*.

Let λ_1, λ_2, λ_3 and λ_4 denote the dual variables, respectively, associated with four constraints of problem ($\mathcal{P}3.2$), the equality constraint in (25b), the SINR constraint of Eve in (25c), the SINR constraint of D_s in (25d), the power constraint in (25e). Then the Lagrangian function of problem ($\mathcal{P}3.2$) is given by

$$\begin{aligned}\mathcal{L}\left(\bar{\mathbf{W}}_1,\bar{\mathbf{W}}_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,t,\gamma_e\right)&=Tr\left(\mathbf{A}\bar{\mathbf{W}}_1\right)\\&+Tr\left(\mathbf{B}\bar{\mathbf{W}}_2\right)+Ct+\lambda_1,\end{aligned} \tag{26}$$

where

$$\begin{aligned}\mathbf{A}=(1-\rho)\,a\mathbf{H}_{SD_p}&-\lambda_2\,(1-\rho)\,a\mathbf{H}_{SE}\\&-\lambda_3\gamma_{\min}\,(1-\rho)\,a\mathbf{H}_{SD_s}-\lambda_4,\end{aligned} \tag{27}$$

$$\begin{aligned}\mathbf{B}=-\lambda_1\,(1-\rho)\,a\mathbf{H}_{SD_p}&+\lambda_2\gamma_e\,(1-\rho)\,a\mathbf{H}_{SE}\\&+\lambda_3\,(1-\rho)\,a\mathbf{H}_{SD_s}-\lambda_4,\end{aligned} \tag{28}$$

$$C=-\lambda_1\sigma_{D_p}^2+\lambda_2\gamma_e\sigma_{E_2}^2-\lambda_3\gamma_{\min}\sigma_{D_s}^2+\lambda_4. \tag{29}$$

The Largrangian dual function is expressed as

$$\begin{aligned}&g\left(\lambda_1,\lambda_2,\lambda_3,\lambda_4,\gamma_e\right)=\\&\max_{\bar{\mathbf{W}}_1\ge 0,\bar{\mathbf{W}}_2\ge 0,t>0}\mathcal{L}\left(\bar{\mathbf{W}}_1,\bar{\mathbf{W}}_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,t,\gamma_e\right).\end{aligned} \tag{30}$$

Since problem ($\mathcal{P}3.2$) is convex and satisfies the Slater's condition, the strong duality holds [20]. Thus, $g_1\left(\gamma_e\right) = \min\limits_{\lambda_1,\lambda_2\ge 0,\lambda_3\ge 0,\lambda_4\ge 0} g\left(\lambda_1,\lambda_2,\lambda_3,\lambda_4,\gamma_e\right)$.

According to [17], $G(\gamma_e)=\log_2\left(\frac{1+g_1(\gamma_e)}{1+\gamma_{E_1}+\gamma_e}\right)$ over $\gamma_e > 0$ has only one single maximum point and the optimal γ_e^* can be found via the one-dimensional search. Based on $G(\gamma_e)$, the gradient of γ_e is expressed as

$$\frac{dG(\gamma_e)}{d\gamma_e}=\frac{\frac{dg_1(\gamma_e)}{d\gamma_e}\left(1+\gamma_{E_1}+\gamma_e\right)-\left(1+g_1(\gamma_e)\right)}{\left(1+g_1(\gamma_e)\right)\left(1+\gamma_{E_1}+\gamma_e\right)\ln 2}, \tag{31}$$

where based on (26),

$$\frac{dg_1(\gamma_e)}{d\gamma_e}=\lambda_2^*\,(1-\rho)\,aTr\left(\mathbf{H}_{SE}\bar{\mathbf{W}}_2\right)+\lambda_2^* t^*\sigma_{E_2}^2, \tag{32}$$

where λ_1^*, λ_2^*, λ_3^* and λ_4^* denote the optimal variables for a given γ_e.

Until now, the optimal solution to problem ($\mathcal{P}1$) with fixed ρ is derived. Next, we will find the optimal ρ by using the equation relationship $\gamma_S = \gamma_{D_p}$.

It is easy to check that γ_S increases with ρ and γ_{D_p} decreases with ρ. In addition, $\gamma_S^{\max} > \gamma_{D_p}^{\min}$ and $\gamma_S^{\min} < \gamma_{D_p}^{\max}$. Therefore, we can define the function

$$h\left(\rho\right)=\gamma_{D_p}-\gamma_S. \tag{33}$$

It is easily observed $h(\rho)$ decreases with ρ, and there must exist only one single wise point making $h(\rho) = 0$. We can find the optimal value of ρ through the one-dimensional search. Above all, problem can be solved in three steps: (1) Given ρ and γ_e, we firstly solve the problem ($\mathcal{P}3$). (2) Then, we use one-dimensional search to find the optimal γ_e. (3) Finally, we use bisection method to find optimal ρ. Repeat these three procedures until problem converges. Detailed steps are summarized in Algorithm 1.

Algorithm 1 Optimal solution to problem $\mathcal{P}1$

Initialize $\rho^{\min}$, $\rho^{\max}$ and tolerance δ;
while $\rho^{\max} - \rho^{\min} > \delta$ **do**
  $\rho \leftarrow \left(\rho^{\max} + \rho^{\min}\right)/2$;
  Initialize $\gamma_e^{\min}$, $\gamma_e^{\max}$ and tolerance ε;
  while $\gamma_e^{\max} - \gamma_e^{\min} > \varepsilon$ **do**
    $\gamma_e \leftarrow \left(\gamma_e^{\max} + \gamma_e^{\min}\right)/2$;
    Solve the problem $\mathcal{P}3.2$ via CVX to obtain λ_1^*, λ_2^*, λ_3^*, λ_4^*, t^*, $\bar{\mathbf{W}}_1^*$, $\bar{\mathbf{W}}_2^*$;
    Calculate $\frac{dG(\gamma_e)}{d\gamma_e}$ according to (31) and (32);
    if $\frac{dG(\gamma_e)}{d\gamma_e} \geq 0$ **then**
      $\gamma_e^{\min} \leftarrow \gamma_e$;
    else
      $\gamma_e^{\max} \leftarrow \gamma_e$;
    end if
  end while
  return $\mathbf{W}_1^* = \bar{\mathbf{W}}_1^*/t^*$,$\mathbf{W}_2^* = \bar{\mathbf{W}}_2^*/t^*$
  return $\mathbf{w}_1^*$ and $\mathbf{w}_2^*$ via EVD of $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$, respectively;
  Calculate $h(\rho)$ according to (33);
  if $h(\rho) \geq 0$ **then**
    $\rho^{\min} \leftarrow \rho$;
  else
    $\rho^{\max} \leftarrow \rho$;
  end if
end while

IV. Simulation Results

In this section, we evaluate the performance of our proposed scheme through numerical simulations. For simplicity, all the received noise power is assumed to $1mW$. Unless other specified, other simulation parameters are set as follows. We assume that node S is equipped with $M = 4$ antennas, while other nodes are equipped with single antenna. The distance between S and Eve is set to $6m$, other distances are all set to $4m$. We assume the path-loss exponent is 2. All channel vectors are randomly generated from i.i.d Rayleigh fading with their respective average power values. The energy harvesting efficiency is set as 0.8, i.e., η=0.8. The transmission power of P and D_p is set to $P_P = 30\ dBm$, $P_D = 30\ dBm$. For comparison, in the first numerical example, we also consider the physical layer security combined SWIPT in CR system without jamming transfer from destination (i.e. D_p), which is labeled as 'No D_p-assisted'.

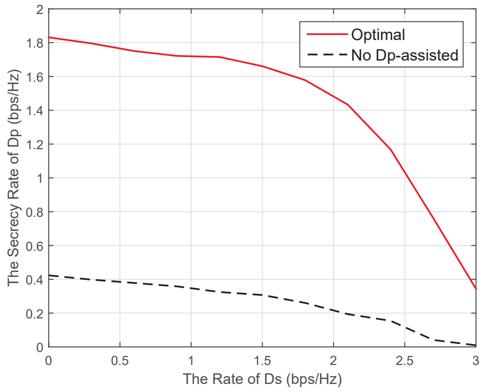

Fig. 2. Nodes D_p-D_s rate region for different schemes.

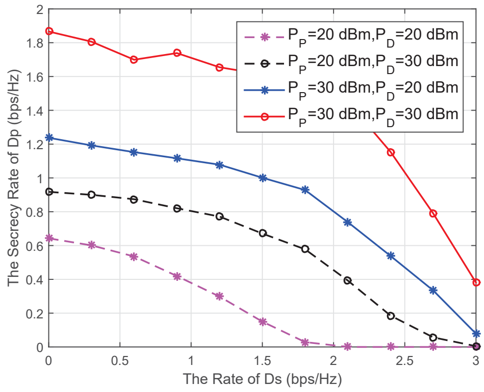

Fig. 3. Nodes D_p-D_s rate region for different power at P and S.

In Fig.2, it is observed that proposed 'optimal' scheme achieves significantly larger rate region than the 'No D_p-assisted' scheme. The reason is as follows. First of all, the jamming signal transmitted by D_p can interfere with the eavesdropper to reduce SINR at Eve. Especially in the first phase, when the channel of eavesdropper is better, legitimate information is easy to be eavesdropped if there is no interference. Then, S can harvest energy from the jamming signal.

The achieved secrecy rate is given as a function of the rate demand at D_s in Fig.3. Observing from this figure, we can see that with the increasing of the rate demand at D_s, all rate curves present a downward trend. This is owing to the fact that the power should be allocated to beamforming vector $\mathbf{w}_2$ to firstly satisfy the rate demand of D_s. Therefore, when the D_s demand increases, the power allocated to the D_p will be reduced, resulting in a decline in the secrecy rate. In addition, we can also note that with the increasing of transmission power at P and D_p, the secrecy rate is greatly enlarged.

Interestingly, the secrecy rate of D_p is not always improved as the transmission power at P increases. The impact of transmission power at P on the achieved secrecy rate is shown in Fig.4. It can be easily observed that, with the increase of transmission power at P, the achieved secrecy rates firstly increase and then decrease. This is mainly due to the fact that at the beginning the power is not enough to meet the rate

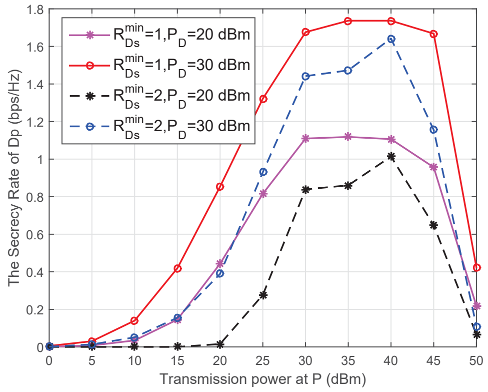

Fig. 4. Secrecy rate of D_p versus transmission power at P.

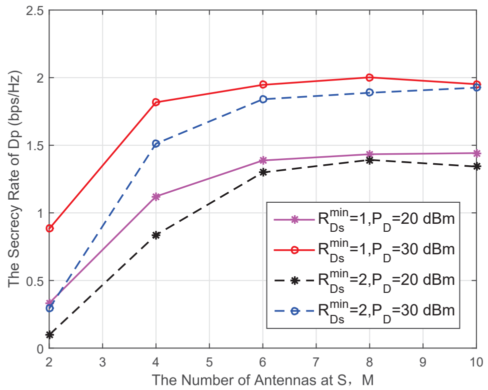

Fig. 5. Secrecy rate of D_p versus the number of antennas at S.

requirements resulting in a relatively low rate. Since the Eve is disturbed by the jamming signal, the secrecy rate increases as the power increases. But when the power is particularly large, the Eve can eavesdrop the information of legitimate user P easily, especially in the first phase due to the fixed power of jamming signal, so there is a falling curve. In addition, it can also be observed that the highest points of the curves increase as the transmission power at D_p increases.

Fig.5 compares the secrecy rate of D_p versus the number of antennas at S. As expected, the rate performance of D_p is improved as the number of antennas grows. Yet the growth trend gradually becomes slow.

V. Conclusion

In this paper, we have considered the physical layer security for cognitive radio systems with SWIPT. We have jointly designed the beamforming vectors and power split ratio to maximize the secrecy rate of primary user while satisfying the rate demand of secondary user. A general two-stage procedure has been presented to solve this non-convex problem. Moreover, extensive simulation results are provided to evaluate our proposed scheme.

Acknowledgment

This paper is supported by the National Natural Science Foundation of China (Projects 61372113, 61421061).

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