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Joint Resource Allocation for Wireless Energy Harvesting Enabled Cognitive Sensor Networks

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ABSTRACT In this paper, we consider a cognitive relaying network, where the cognitive sensor transmitter (CST) is capable of harvesting energy from the radio frequency signals with a power splitting scheme. Specifically, the primary transmitter (PT) broadcasts its signal to primary receiver (PR) and CST in the first transmission slot. After receiving PT's signal, CST splits the received signal into two parts, one for information decoding and the other for energy harvesting. In the second transmission slot, CST allocates a part of the accessed bandwidth to forward PT's signal to PR with amplify-and-forward or decode-and-forward relaying protocols by using the harvested energy in the first transmission slot. As a reward, CST can utilize the remained bandwidth to transmit its own signal to the cognitive sensor receiver. The main object is to maximize cognitive network transmission rate by jointly optimizing the power splitting ratio and bandwidth subject to the primary transmission rate constraint. Simulation results are presented to illustrate the performance improvement of both primary and cognitive systems.

INDEX TERMS Wireless energy harvesting, power splitting, bandwidth allocation, cognitive relaying sensor network.

I. INTRODUCTION

Due to the low power consumption, low cost and self-organization characteristics, wireless sensor networks (WSNs) can be extensively used in various fields [1]–[3], e.g., surveillance applications, intrusion detection and structural health monitoring. However, the sensor nodes are always battery-powered in the traditional WSNs. When the energy of the battery is exhausted, the collected information cannot be successfully transmitted to the next node, which leads to performance degradation. Although we can prolong the lifetime of the battery-powered sensor nodes by recharging or replacing equipped batteries. However, this doing might be inconvenient, harmful or even impossible in some difficult-to-access locations. Therefore, it is important to design an efficient power-supply mechanism for prolonging the lifetime of WSNs.

Energy harvesting is considered to be a feasible method to effectively extend the lifetime of WSNs without replacing or recharging the battery equipped in sensor nodes. Sensor nodes can be powered by harvesting energy from the surrounding environment [4]–[6], e.g., thermoelectric and vibration power, wind and solar. However, these ambient energy source are unstable, which cannot provide sustainable energy supply. Also, it is inconvenient to harvest the energy from the surrounding environments, as WSNs may be deployed indoor or underground environment. Different with the EH, wireless power transfer (WPT) enables sensor nodes to charge their batteries from more reliable and stable energy source, e.g., radio-frequency (RF) signals [7], [8]. Moreover, the information and energy can be transferred simultaneously as the RF signals carry both energy and information. simultaneous wireless information and power transfer (SWIPT) is the technology proposed to harvest energy and decode information at the receiver from the same RF signals.

SWIPT technology is considered as a realizable and practical energy charging method for WSNs [9]–[14]. A general framework was proposed for SWIPT WSNs to maximize network performance through optimizing some practical feasible parameters in [10]. Cooperative transmission problem to maximize the network energy-efficient performance for clustered based SWIPT WSNs is studied in [11], in which an energy harvesting relay based on power splitting (PS) protocol is used to aid the information transmission between two adjacent cluster heads. A cooperative SWIPT scheme based on time switching (TS) protocol was proposed to maximize the energy transfer efficiency in multi-hop WSNs [13]. [14] proposed a unified framework to optimize the SWIPT WSNs performance based on TS and PS scheme over Nakagami-m fading channels.

In the meanwhile, another serious problem for WSNs is that WSNs usually operate over the unlicensed spectrum. The unlicensed spectrum becomes more and more crowded with the expand use of wireless services, which makes WSNs suffer heavy interference. To deal with the spectrum scarcity problem, cognitive radio (CR) technique has been extensively studied to effectively improve the spectrum utilization [15]–[19]. Thus, in WSNs, CR technology can be used to enable the sensor nodes opportunistic share the licensed spectrum to transmit their signals through radio configuration adjustment, which refers to the cognitive sensor networks (CSN).

Combining CR with SWIPT, both spectrum efficiency and energy efficiency can be simultaneously improved in CSN [20]–[28]. Reference [23] proposed a SWIPT based cooperation protocol for cognitive network, in which the cognitive user transmits the primary and its own signal by using the harvested energy from the primary user and its own energy. A time-slotted SWIPT based cognitive network is proposed in [24], where the cognitive user exchange for the transmission time to send its own signal by forwarding the primary signal with the harvested energy from the ambient radio signal. Reference [25] studied opportunistic relaying and dynamic SWIPT in cognitive network, where the cognitive user can act as relay to forward primary signal and harvest energy from primary transmission. Through jointly controlling the sampling rates and channel access of the sensor nodes, network utility maximization problem was studied in [26] for energy harvesting CSN.

However, in the existing SWIPT based cognitive sensor network, the cognitive sensor node uses the same bandwidth to transmit primary and cognitive signals, which will cause serious interference to the primary and cognitive systems. Therefore, in this paper, we propose a spectrum sharing protocol in which no interference will be experienced for both primary and cognitive systems. Specifically, the cognitive sensor transmitter (CST) uses a part of the accessed bandwidth to forward the primary signal by using the harvested energy, and uses the remained bandwidth to transmit its own signal. Thus, disjoint bandwidth is used for primary and cognitive signals transmitting, no interference will be caused to each other. We study the joint power splitting ratio and bandwidth optimization to maximize cognitive network transmission rate with the primary transmission rate constraint. Simulation results are presented to illustrate the performance improvement of both primary and cognitive systems.

The main contributions of this paper are summarized as follows.

- We proposed a spectrum sharing protocol in wireless energy harvesting enabled CSN, in which CST forwards the primary signal with a part of the accessed bandwidth by using the harvested energy, and transmit its own signal with the remained bandwidth. No interference will be felt at both of the primary and cognitive systems.
- Joint power splitting ratio and bandwidth allocation is derived, such that the cognitive system transmission rate is maximized, while guaranteeing the primary transmission rate achieving the target rate.
- Simulation results confirm the benefits of the proposed spectrum sharing protocol, and also demonstrate the superiority of the proposed resource allocation strategy over the benchmark strategy.

The remainder of this paper is organized as follows. In Section II, we introduce the system model. The DF and AF problems formulation and their solutions are presented in Sections III and IV, respectively. Simulation results are provided in Section V to illustrate the performance of the proposed spectrum sharing protocol and resource allocation algorithm. Finally we conclude this paper in Section VI.

II. SYSTEM MODEL AND PROPOSED SPECTRUM SHARING PROTOCOL

We consider a wireless energy harvesting enabled CSN, which consists of a primary system and a cognitive sensor system, as shown in Fig. 1. The primary system consists of a primary transmitter (PT) and a primary receiver (PR). The primary system supports the relay function and works on a licensed spectrum W. The cognitive sensor system is composed of a cognitive sensor transmitter (CST) and a cognitive sensor receiver (CSR), which sends its own signal by seeking for an opportunity to share the primary licensed spectrum when the transmission between PT and PR is incapable to achieve the target transmission rate, which may be due to the path loss or shadow fading between PT and PR. CST has energy harvest function, which can harvest energy from RF signals and the harvested energy is stored into a rechargeable battery.

We assume that the channel is a Rayleigh flat fading channel, h_1, h_2, h_3 and h_4 denote the channel coefficients of PT→PR, PT→CST, CST→PR and CST→CSR links, respectively. d_1, d_2, d_3 and d_4 denote the distance of PT→PR, PT→CST, CST→PR and CST→CSR links, respectively. We have $h_i \sim \mathcal{CN}\left(0, d_i^{-\nu}\right)$, $i = 1, 2, 3, 4$, where ν denotes the path loss exponent. $\gamma_i = |h_i|^2$ denotes the instantaneous channel power gain of h_i. We further assume that all the channel coefficients are constant in the two transmission slots. Without loss of generality, we assume that all the noise terms are complex Gaussian random variables with zero mean and variance σ^2.

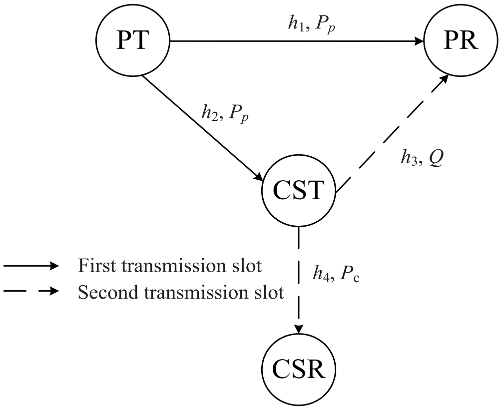

FIGURE 1. **System model.**

The transmission between PT and PR is divided into two transmission slots. In the first transmission slot, PT broadcasts its signal to PR and CST with its transmit power P_p. After receiving PT's signal, CST splits the received signal into two parts, which are used for information decoding and energy harvesting, respectively. In the second transmission slot, PT stops transmission, if CST adopts AF relaying protocol, it amplifies the received signal and then forwards it to PR with a part of the accessed bandwidth by using the harvested energy Q in the first transmission slot. If CST adopts DF relay protocol, it decodes the received signal first and then retransmits it to PR by serving as a trustable relay. As a reward, CST can utilize the remained bandwidth to transmit its own signal to CSR with its transmit power P_c.

III. DECODE-AND-FORWARD STRATEGY

In the first transmission slot, PT sends its signal to CST and PR. CST uses α $(0 < \alpha < 1)$ fraction of the received power to harvest energy and uses the remaind power to decode information. Thus, the achievable rates of PT→PR and PT→CST links can be written as

$$R_d = \frac{1}{2} W \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2} \right) \tag{1}$$

$$R_p^1 = \frac{1}{2} W \log_2 \left(1 + \frac{\alpha P_p \gamma_2}{\sigma^2} \right) \tag{2}$$

And the harvested energy at CST can be written as

$$Q^{DF} = \varepsilon \left(1 - \alpha \right) P_p \gamma_2 \tag{3}$$

where ε denotes the energy harvesting conversion efficiency at CST.

In the second transmission slot, CST allocates a part of the bandwidth bW $(0 < b < 1)$ to forward PT's signal to PR with the harvested energy Q^{DF}. Then the achievable rate at PR can be written as

$$R_p^2 = \frac{1}{2} bW \log_2 \left(1 + \frac{\varepsilon \left(1 - \alpha \right) P_p \gamma_2 \gamma_3}{\sigma^2} + \frac{P_p \gamma_1}{\sigma^2} \right) + \frac{1}{2} (1 - b) W \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2} \right) \tag{4}$$

The first term is obtained by using maximal ratio combination (MRC) through two transmission slot over the b fraction of the bandwidth, and the second term is obtained from PT's direct transmission in the first transmission slot.

After two transmission slot, the achievable rate of the primary system is

$$R_p^{DF} = \min\{R_p^1, R_p^2\} \tag{5}$$

Meanwhile, CST transmits its own signal to CSR by using the remaining $(1 - b)W$ bandwidth and its own power. Therefore, the achievable rate of cognitive system can be written as

$$R_c^{DF} = \frac{1}{2} (1 - b) W \log_2 \left(1 + \frac{P_c \gamma_4}{\sigma^2} \right) \tag{6}$$

A. PROBLEM FORMULATION

With the objective of maximizing the achievable rate of cognitive system by joint optimization of power splitting ratio and bandwidth, subject to a given primary target transmission rate constraint, the following optimization problem is formulated.

$$\max_{\alpha, b} R_c^{DF} = \frac{1}{2} (1 - b) W \log_2 \left(1 + \frac{P_c \gamma_4}{\sigma^2} \right) \tag{7}$$

subject to

$$\begin{cases} R_p^{DF} \geq R_T \\ 0 < \alpha < 1 \\ 0 < b < 1 \end{cases} \tag{8}$$

where R_T denotes the primary target transmission rate.

B. OPTIMAL SOLUTION

To satisfy the first condition of (8), we can obtain (9) as shown in the bottom of this page and

$$\frac{1}{2} W \log_2 \left(1 + \frac{\alpha P_p \gamma_2}{\sigma^2} \right) \geq R_T \tag{10}$$

Make some algebraic transformation of (9) and (10), we can obtain

$$\left\{ \begin{array}{l} \alpha \geq \alpha_1 = \dfrac{\sigma^2 M}{\gamma_2 P_p} \\ b \geq \dfrac{2R_T - W \log_2 \left(1 + \dfrac{P_p \gamma_1}{\sigma^2} \right)}{W \log_2 \left(1 + \dfrac{\varepsilon (1 - \alpha) P_p \gamma_2 \gamma_3}{\sigma^2 + P_p \gamma_1} \right)} \end{array} \right. \tag{11}$$

where $M = 2^{\frac{2R_T}{W}} - 1$.

$$\frac{1}{2} bW \log_2 \left(1 + \frac{\varepsilon \left(1 - \alpha \right) P_p \gamma_2 \gamma_3}{\sigma^2} + \frac{P_p \gamma_1}{\sigma^2} \right) + \frac{1}{2} (1 - b) W \log_2 \left(1 + \frac{P_p \gamma_1}{\sigma^2} \right) \geq R_T \tag{9}$$

To make b satisfy $0 < b < 1$, we can obtain

$$\alpha \le \alpha_2 = 1 - \frac{\sigma^2 M - P_p\gamma_1}{\varepsilon P_p\gamma_2\gamma_3} \tag{12}$$

$$\frac{1}{2}W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right) < R_T \tag{13}$$

In (11), we can find that b is a monotonically increasing function of α. And from (6), it is easy to observe that R_c^{DF} is a monotonically decreasing function of b. Thus, the optimal power splitting ratio and bandwidth allocation of the optimization problem can be written as

$$b^* = \frac{2R_T - W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)}{W\log_2\left(1+\frac{\varepsilon(1-\alpha)P_p\gamma_2\gamma_3}{\sigma^2+P_p\gamma_1}\right)} \tag{14}$$

$$\alpha^* = \alpha_1 = \frac{\sigma^2 M}{\gamma_2 P_p} \tag{15}$$

Substituting α^* into (14), we can obtain the optimal b^* as

$$b^* = \frac{2R_T - W\log_2\left(1+\frac{P_P\gamma_1}{\sigma^2}\right)}{W\log_2\left(1+\frac{\varepsilon\gamma_3\left(P_P\gamma_2-\sigma^2 M\right)}{\sigma^2+P_P\gamma_1}\right)} \tag{16}$$

IV. AMPLIFY-AND-FORWARD STRATEGY

If CST adopts AF strategy, it will amplify the received signal and then forward it to PR. In the first transmission slot, the received signal at PR and CST can be written as

$$y_{pr1} = \sqrt{P_p}h_1x_1 + n_1 \tag{17}$$

$$y_{cst} = \sqrt{P_p}h_2x_1 + n_2 \tag{18}$$

where x_1 is the normalized signal transmitted by PT, n_1 and n_2 are the additive white Gaussian noise received at PR and CST in the first transmission slot.

CST splits $1-\alpha$ fraction of the received power to harvested energy. Thus, the harvest energy at CST can be written as

$$Q^{AF} = \varepsilon\left(1-\alpha\right)P_p\gamma_2 \tag{19}$$

In the second transmission slot, CST amplifies the received signal and forwards it to PR by using the harvest energy and b fraction of the bandwidth. The received signal at PR in the second transmission slot can be written as

$$y_{pr2} = \phi y_{cst}h_3 + n_3 \tag{20}$$

where n_3 is the additive white Gaussian noise received at PR in the second transmission slot, and ϕ is the amplification factor of CST, which can be written as

$$\phi = \sqrt{\frac{\varepsilon(1-\alpha)P_p\gamma_2}{\alpha P_p\gamma_2+\sigma^2}} \tag{21}$$

Substituting (18) and (21) into (20), we can obtain

$$y_{pr2} = \sqrt{\frac{\alpha P_p\varepsilon(1-\alpha)P_p\gamma_2}{\alpha P_p\gamma_2+\sigma^2}}h_2h_3x_1 + n_3 + \sqrt{\frac{\varepsilon(1-\alpha)P_p\gamma_2}{\alpha P_p\gamma_2+\sigma^2}}h_3n_2 \tag{22}$$

Thus, the signal-to-noise ratio (SNR) between PT to PR link with the help of CST can be written as

$$SNR = \frac{\alpha P_p^2\gamma_2\varepsilon(1-\alpha)\gamma_2\gamma_3}{\sigma^2(\sigma^2+\alpha P_p\gamma_2+\varepsilon(1-\alpha)P_p\gamma_2\gamma_3)} \approx \frac{\alpha P_p^2\gamma_2\varepsilon(1-\alpha)\gamma_2\gamma_3}{\sigma^2(\alpha P_p\gamma_2+\varepsilon(1-\alpha)P_p\gamma_2\gamma_3)} \tag{23}$$

Then the achievable rate of primary system over two transmission slots can be written as

$$R_p^{AF} = \frac{1}{2}bW\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}+\frac{\alpha P_p^2\gamma_2\varepsilon(1-\alpha)\gamma_2\gamma_3}{\sigma^2(\alpha P_p\gamma_2+\varepsilon(1-\alpha)P_p\gamma_2\gamma_3)}\right) + \frac{1}{2}(1-b)W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right) \tag{24}$$

In the second transmission slot, CST uses the remaind $(1-b)W$ bandwidth and its own power to transmits its own signal to CSR. The achievable rate of cognitive system can be written as

$$R_c^{AF} = \frac{1}{2}(1-b)W\log_2\left(1+\frac{P_c\gamma_4}{\sigma^2}\right) \tag{25}$$

A. PROBLEM FORMULATION

With AF strategy, the optimization problem can be formulated as

$$\max_{\alpha,b} R_c^{AF} = \frac{1}{2}(1-b)W\log_2\left(1+\frac{P_c\gamma_4}{\sigma^2}\right) \tag{26}$$

subject to

$$\begin{cases} R_p^{AF} \ge R_T \\ 0 < \alpha < 1 \\ 0 < b < 1 \end{cases} \tag{27}$$

B. OPTIMAL SOLUTION

To satisfy the first condition of (27), we can obtain

$$b \ge \frac{2R_T - W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)}{W\log_2\left(1+\frac{\alpha P_p^2\gamma_2\varepsilon(1-\alpha)\gamma_2\gamma_3}{(\alpha P_p\gamma_2+\varepsilon(1-\alpha)P_p\gamma_2\gamma_3)(\sigma^2+P_p\gamma_1)}\right)} \tag{28}$$

From (25), we can find that R_c^{AF} is a monotonically decreasing function of b. Thus, the optimal bandwidth allocation can be written as

$$b^* = \frac{2R_T - W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)}{W\log_2\left(1+\frac{g(\alpha)}{(\sigma^2+P_p\gamma_1)}\right)} \tag{29}$$

where

$$g(\alpha)=\frac{\alpha P_p^2\gamma_2\varepsilon(1-\alpha)\gamma_2\gamma_3}{\alpha P_p\gamma_2\sigma^2+\varepsilon(1-\alpha)P_p\gamma_2\gamma_3\sigma^2} \tag{30}$$

To make b^* satisfy $0<b^*<1$, we can obtain

$$\frac{1}{2}W\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)<R_T \tag{31}$$

$$f(\alpha)>0 \tag{32}$$

where

$$f(\alpha)=-\frac{P_p\gamma_2}{\sigma^2}\varepsilon\gamma_3\alpha^2-H\varepsilon\gamma_3+\left(\frac{P_p\gamma_2}{\sigma^2}\varepsilon\gamma_3-H+H\varepsilon\gamma_3\right)\alpha, \tag{33}$$

where $H=\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)\left(M-1-\frac{P_p\gamma_1}{\sigma^2}\right)$.

To make $f(\alpha)>0$, it is easy to obtain

$$\alpha_3<\alpha<\alpha_4 \tag{34}$$

where

$$\alpha_3=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3+\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3} \tag{35}$$

$$\alpha_4=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3-\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3}, \tag{36}$$

where

$$\Delta=\left(\frac{P_p\gamma_2\gamma_3\varepsilon}{\sigma^2}\right)^2+H^2+(H\gamma_3\varepsilon)^2-2H\frac{P_p\gamma_2\gamma_3\varepsilon}{\sigma^2}-H\gamma_3\varepsilon\frac{P_p\gamma_2\gamma_3\varepsilon}{\sigma^2}-2H^2\gamma_3\varepsilon \tag{37}$$

In (29), we can find that the optimal b^* is a decreasing function of $g(\alpha)$. Thus, to make b^* obtain the minimum value, we need to get an optimal value of α to let $g(\alpha)$ achieve its maximum value.

Take the first derivation of $g(\alpha)$ with α, we can obtain

$$g'(\alpha)=\frac{\varepsilon P_p\gamma_2\gamma_3\sigma^2 t(\alpha)}{(\alpha P_p\gamma_2+(1-\alpha)\varepsilon P_p\gamma_2\gamma_3)^2} \tag{38}$$

where

$$t(\alpha)=(\varepsilon\gamma_3-1)\alpha^2-2\varepsilon\gamma_3\alpha+\varepsilon\gamma_3 \tag{39}$$

From (38), we can find that the denominator of $g'(\alpha)$ is always positive. Thus, the monotonicity of $g(\alpha)$ only depends on $t(\alpha)$. Let $t(\alpha)=0$, we can obtain two roots

$$\alpha_5=\frac{\varepsilon\gamma_3-\sqrt{\varepsilon\gamma_3}}{\varepsilon\gamma_3-1} \tag{40}$$

$$\alpha_6=\frac{\varepsilon\gamma_3+\sqrt{\varepsilon\gamma_3}}{\varepsilon\gamma_3-1} \tag{41}$$

In (40) and (41), we can find that whether α_5 and α_6 are positive or negative depend on $\varepsilon\gamma_3-1$.

Case 1: when $\varepsilon\gamma_3-1<0$

It is easy to find that $0<\alpha_5<1$ and $\alpha_6<0$. As $t(\alpha)$ is a quadratic convex function of α, then, we can observe that $g(\alpha)$ monotonically increases in $[0,\alpha_5]$ and decreases in $[\alpha_5,1]$. Thus, the optimal value of α can be obtained by analyzing the relative value among α_5, α_3 and α_4.

(1) when $\alpha_5<\alpha_3<\alpha_4$, $g(\alpha)$ monotonically decreases in $[\alpha_3,\alpha_4]$. Thus, $g(\alpha)$ obtains its maximum value when $\alpha=\alpha_3$. Then, the optimal value of α can be written as

$$\alpha^*=\alpha_3=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3+\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3} \tag{42}$$

(2) when $\alpha_3<\alpha_5<\alpha_4$, $g(\alpha)$ monotonically increases in $[\alpha_3,\alpha_5]$ and decreases in $[\alpha_5,\alpha_4]$. Thus, $g(\alpha)$ obtains its maximum value when $\alpha=\alpha_5$. Then, the optimal value of α can be written as

$$\alpha^*=\alpha_5=\frac{\varepsilon\gamma_3-\sqrt{\varepsilon\gamma_3}}{\varepsilon\gamma_3-1} \tag{43}$$

(3) when $\alpha_4<\alpha_5<1$, $g(\alpha)$ monotonically increases in $[\alpha_3,\alpha_4]$. Thus, $g(\alpha)$ obtains its maximum value when $\alpha=\alpha_4$. Then, the optimal value of α can be written as

$$\alpha^*=\alpha_4=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3-\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3} \tag{44}$$

Case 2: when $\varepsilon\gamma_3-1>0$

It is easy to find that $0<\alpha_5<1$ and $\alpha_6>1$. As $t(\alpha)$ is a quadratic concave function of α, then, we can observe that $g(\alpha)$ monotonically increases in $[0,\alpha_5]$ and decreases in $[\alpha_5,1]$. With the similar analysis in **Case 1** we can obtain the optimal value of α.

(1) when $\alpha_5<\alpha_3<\alpha_4$, the optimal value of α can be written as

$$\alpha^*=\alpha_3=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3+\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3} \tag{45}$$

(2) when $\alpha_3<\alpha_5<\alpha_4$, the optimal value of α can be written as

$$\alpha^*=\alpha_5=\frac{\varepsilon\gamma_3-\sqrt{\varepsilon\gamma_3}}{\varepsilon\gamma_3-1} \tag{46}$$

(3) when $\alpha_4<\alpha_5<1$, the optimal value of α can be written as

$$\alpha^*=\alpha_4=\frac{\varepsilon P_p\gamma_2\gamma_3-\left(H-H\varepsilon\gamma_3-\sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p\gamma_2\gamma_3} \tag{47}$$

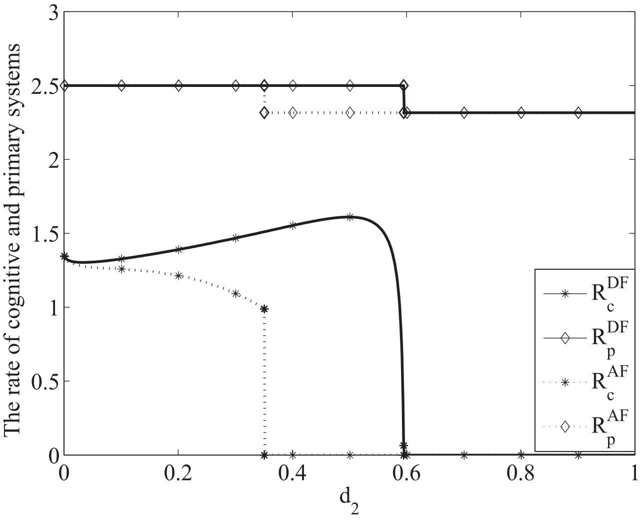

FIGURE 2. The rate of primary and cognitive system versus d_2.

Concluded from the analysis in **Case 1** and **Case 2**, the optimal value of α can be summarized as

$$\alpha^* = \begin{cases} \alpha_3 = \dfrac{\varepsilon P_p \gamma_2 \gamma_3 - \left(H - H\varepsilon\gamma_3 + \sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p \gamma_2 \gamma_3}, \\ \qquad\qquad \alpha_5 < \alpha_3 < \alpha_4 \\ \alpha_5 = \dfrac{\varepsilon\gamma_3 - \sqrt{\varepsilon\gamma_3}}{\varepsilon\gamma_3 - 1}, \quad \alpha_3 < \alpha_5 < \alpha_4 \\ \alpha_4 = \dfrac{\varepsilon P_p \gamma_2 \gamma_3 - \left(H - H\varepsilon\gamma_3 - \sqrt{\Delta}\right)\sigma^2}{2\varepsilon P_p \gamma_2 \gamma_3}, \\ \qquad\qquad \alpha_4 < \alpha_5 < 1 \end{cases} \tag{48}$$

V. SIMULATION RESULTS

We consider PT, PR, CST and CSR are in a two-dimensional X-Y plane, where PT and PR are located at points (0, 0) and (1, 0), respectively, thus $d_1 = 1$. CST moves on the positive X axis from PT to CST, its coordinate is $(d_2, 0)$. CSR is located at (1, -0.5). Thus, $d_3 = 1 - d_2$, and $d_4 = \sqrt{d_2^2 + 0.25}$. Unless otherwise specified, the path loss exponent $v = 4$, $\sigma^2 = 1$, $R_T = 2.5bps/Hz$, $P_p = 6dB$, $P_c = 10dB$, $W = 1$, ε=1.

Fig. 2 shows the rate of primary and cognitive system with DF and AF relaying protocols versus d_2. We can observe from Fig. 2 that in the access region, the primary system of DF and AF relaying protocol can achieve its target rate. The access region is defined as the region where the CST can access to the primary spectrum. The cognitive rate and access region of DF relaying protocol is larger than AF relaying protocol, which is due to that in AF relaying protocl, the noise will also be amplified at CST. From Fig. 2, we can alos observe that when CST moves farther away from PT, the primary system cannot achieve its target rate. It is because that when the distance between PT and CST becomes larger, less energy can be harvested at CST, which leads CST do not have enough power to help forward the primary signal to PR achieving the target rate. Then, the cognitive system will not be permitted to access to the primary spectrum.

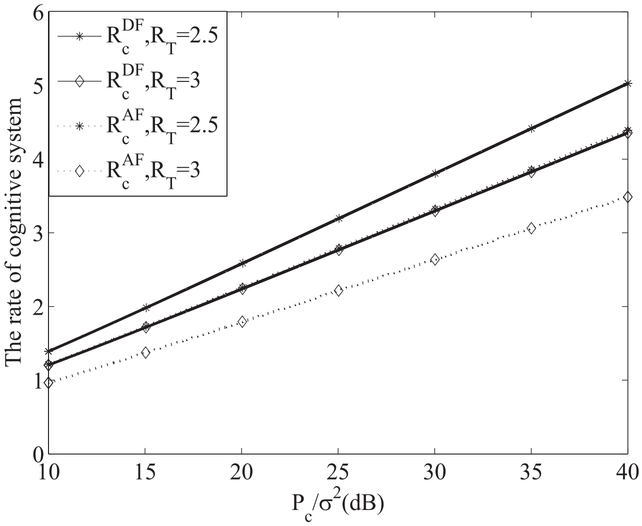

FIGURE 3. The rate of cognitive system versus P_c with different primary target rate.

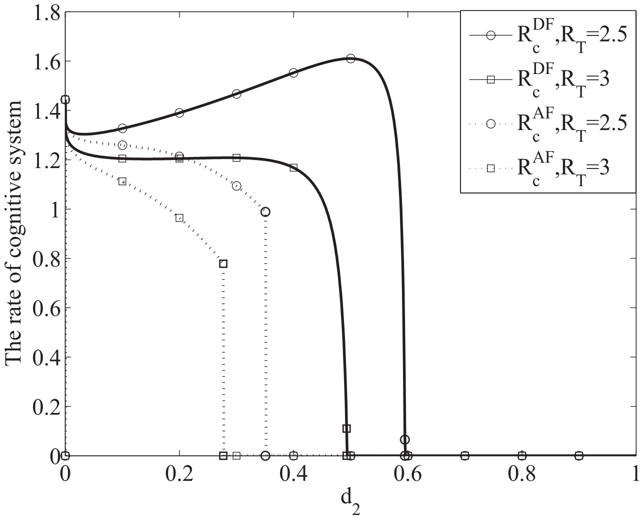

FIGURE 4. The rate of cognitive system versus d_2 with different primary target rate.

Fig. 3 and Fig. 4 shows the rate of cognitive system versus the cognitive transmit power P_c and d_2, respectively, with different primary target rate R_T. In Fig. 3, $d_2 = 0.2$, we can find that when the cognitive transmit power P_c becomes larger the rate of cognitive system will also becomes larger, which is because that CST uses its own power P_c to transmit its own signal to CSR. We can observe from Fig. 3 and Fig. 4 that the rate of cognitive system with DF and AF relaying protocol will be smaller when the primary target rate R_T becomes larger. It is because that when R_T becomes larger, CST needs to allocate more bandwidth to forward the primary signal, which results less bandwidth can be used to transmit its own signal.

Fig. 5 clearly shows that our proposed spectrum sharing protocol significantly outperforms the spectrum sharing protocol in [22] with different cognitive transmit power P_c. In the spectrum sharing protocol proposed in [22], CST uses

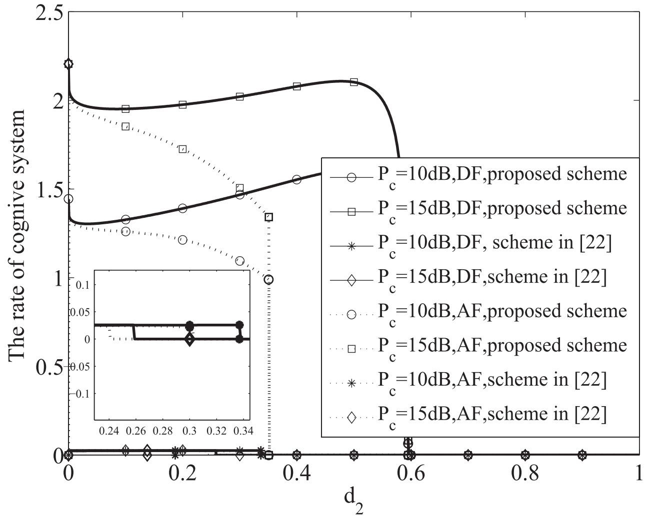

FIGURE 5. **The rate of cognitive system versus d_2 with different cognitive target rate.**

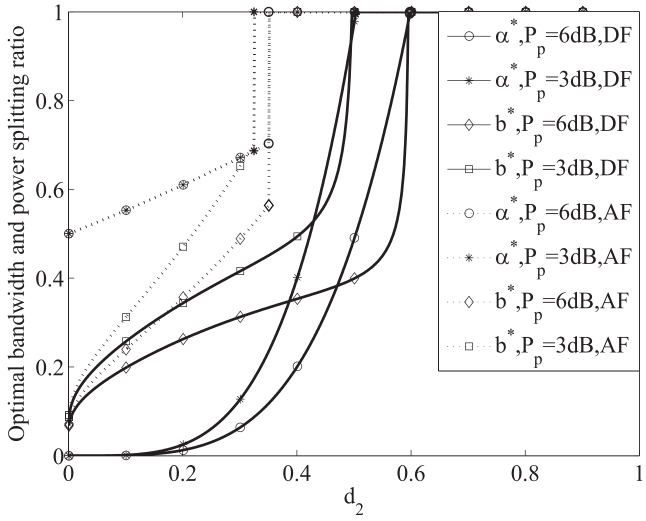

FIGURE 6. **Optimal bandwidth and power splitting ratio versus d_2 with different primary transmit power.**

the same bandwidth to transmit the primary and its own signals, which will result the primary and cognitive system interfere with each other. Thus, the rate of cognitive system is much smaller than our proposed spectrum sharing protocol. In Fig. 5, we can also observe that the access region of the cognitive system is same with different cognitive transmit power. It is because that the cognitive access region will only be limited by the primary transmit power P_p and primary target rate R_T, which can be observed from Fig. 6 and Fig. 7.

Fig. 6 and Fig. 7 shows optimal bandwidth and power splitting ratio versus d_2 with different primary transmit power P_p and primary target rate R_T, respectively. We can observe from Fig. 6 that when P_p becomes smaller, the cognitive access region will also be smaller, which is because that when P_p becomes smaller, CST will harvest less energy in the first transmission slot to help forward the primary signal. We can

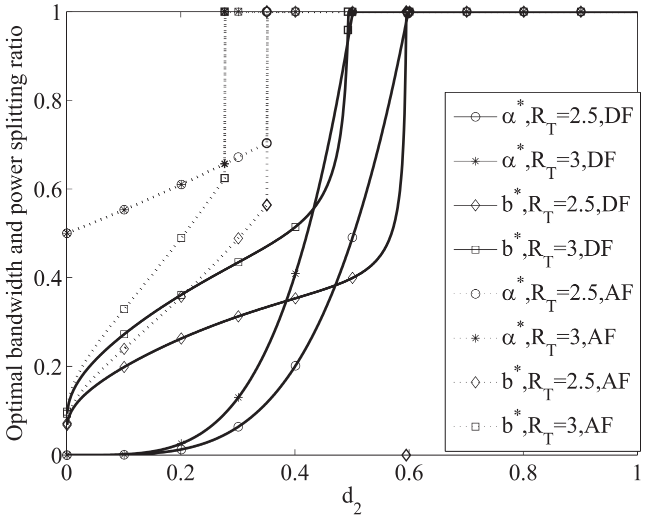

FIGURE 7. **Optimal bandwidth and power splitting ratio versus d_2 with different primary target rate.**

also observe from Fig. 6 that when d_2 becomes larger, more received power at CST in the first transmission slot will be split to decode information and more bandwidth will be allocated to forward the primary signal in the second transmission slot. In Fig. 7, we can observe that the cognitive access region will becomes larger when R_T becomes smaller, which is because that CST need less power to forward the primary signal with smaller R_T. We can also observe from Fig. 7 that more received power at CST in the first transmission slot will be split to decode information and less bandwidth will be allocated to forward the primary signal in the second transmission slot with smaller R_T.

VI. CONCLUSION

In this paper, we propose a spectrum sharing protocol in wireless energy harvesting enabled CSN. Specifically, CST splits the received signal into two independent parts in the first transmission slot, which are used for information decoding and energy harvesting, respectively. In the second transmission slot, CST allocates a part of the accessed bandwidth to forward the primary signal by using the harvested energy, and transmit its own signal with the remained bandwidth. No interference will be felt at both of the primary and cognitive systems. Joint power splitting ratio and bandwidth allocation is investigated to maximize the rate of cognitive system subject to the primary transmission rate constraint.

REFERENCES

[1] T.-L. Chin and W.-C. Chuang, "Latency of collaborative target detection for surveillance sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 26, no. 2, pp. 467–477, Feb. 2015.

[2] A. Bagula, L. Castelli, and M. Zennaro, "On the design of smart parking networks in the smart cities: An optimal sensor placement model," *Sensors*, vol. 15, no. 7, pp. 15443–15467, 2015.

[3] L. P. Qian, Y. J. A. Zhang, J. Huang, and Y. Wu, "Demand response management via real-time electricity price control in smart grids," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 7, pp. 1268–1280, Jul. 2013.

[4] S. Yang, X. Yang, J. A. McCann, T. Zhang, G. Liu, and Z. Liu, "Distributed networking in autonomic solar powered wireless sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 12, pp. 750–761, Dec. 2013.

[5] L. P. Qian, G. Feng, and V. C. M. Leung, "Optimal transmission policies for relay communication networks with ambient energy harvesting relays," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3754–3768, Dec. 2016.

[6] T. Moustafa and W. Moreno, "RAM air and wind energy harvesting survey for electrical vehicles and transportation," in *Proc. SoutheastCon*, Charlotte, NC, USA, Mar./Apr. 2017, pp. 1–7.

[7] N. Zhao, F. R. Yu, and V. C. M. Leung, "Opportunistic communications in interference alignment networks with wireless power transfer," *IEEE Wireless Commun.*, vol. 22, no. 1, pp. 88–95, Feb. 2015.

[8] W. D. Lu, Y. Gong, J. Y. Wu, H. Peng, and J. Y. Hua, "Simultaneous wireless information and power transfer based on joint subcarrier and power allocation in OFDM systems," *IEEE Access*, vol. 5, pp. 2763–2770, 2017.

[9] S. Kisseleff, X. Chen, I. F. Akyildiz, and W. H. Gerstacker, "Efficient charging of access limited wireless underground sensor networks," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 2130–2142, May 2016.

[10] A. Mehrabi and K. Kim, "General framework for network throughput maximization in sink-based energy harvesting wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 7, pp. 1881–1896, Jul. 2017.

[11] S. Guo, F. Wang, Y. Yang, and B. Xiao, "Energy-efficient cooperative transmission for simultaneous wireless information and power transfer in clustered wireless sensor networks," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4405–4417, Nov. 2015.

[12] Y. Liu and X. Wang, "Information and energy cooperation in OFDM relaying: Protocols and optimization," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5088–5098, Jul. 2016.

[13] T. Liu, X. D. Wang, and L. Zheng, "A cooperative SWIPT scheme for wirelessly powered sensor networks," *IEEE Trans. Commun.*, vol. 65, no. 6, pp. 2740–2752, Jun. 2017.

[14] G. Pan, H. Lei, Y. Yuan, and Z. Ding, "Performance analysis and optimization for SWIPT wireless sensor networks," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2291–2302, May 2017.

[15] X. Li, N. Zhao, Y. Sun, and F. R. Yu, "Interference alignment based on antenna selection with imperfect channel state information in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5497–5511, Jul. 2016.

[16] W. Lu, Y. J. Zhang, M. Wang, X. Liu, and J. Hua, "Cooperative spectrum sharing in OFDM two-way relay systems with bidirectional transmissions," *IEEE Commun. Lett.*, vol. 21, no. 6, pp. 1349–1352, Jun. 2017.

[17] N. Zhao, F. R. Yu, H. Sun, and M. Li, "Adaptive power allocation schemes for spectrum sharing in interference-alignment-based cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3700–3714, May 2016.

[18] S. Hu, G. Bi, Y. L. Guan, and S. Li, "TDCS-based cognitive radio networks with multiuser interference avoidance," *IEEE Trans. Commun.*, vol. 61, no. 12, pp. 4828–4835, Dec. 2013.

[19] W. Lu, Y. Gong, S. H. Ting, X. L. Wu, and N. T. Zhang, "Cooperative OFDM relaying for opportunistic spectrum sharing: Protocol design and resource allocation," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2126–2135, Jun. 2012.

[20] F. Zhou, N. C. Beaulieu, J. Cheng, Z. Chu, and Y. Wang, "Robust max–min fairness resource allocation in sensing-based wideband cognitive radio with SWIPT: Imperfect channel sensing," *IEEE Syst. J.*, to be published.

[21] Y. Yuan and Z. Ding, "Outage constrained secrecy rate maximization design with SWIPT in MIMO-CR systems," *IEEE Trans. Veh. Technol.*, to be published.

[22] J. Wu, W. Lu, H. Peng, and X. Liu, "Spectrum access based on energy harvesting with optimal power allocation," in *Proc. Int. Conf. Commun. Netw. China*, 2016, pp. 551–559.

[23] 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.

[24] S. Yin, E. Zhang, Z. Qu, L. Yin, and S. Li, "Optimal cooperation strategy in cognitive radio systems with energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 13, no. 9, pp. 4693–4707, Sep. 2014.

[25] J. Yan and Y. Liu, "A dynamic SWIPT approach for cooperative cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11122–11136, Dec. 2017.

[26] J. Ren, Y. Zhang, R. Deng, N. Zhang, D. Zhang, and X. Shen, "Joint channel access and sampling rate control in energy harvesting cognitive radio sensor networks," *IEEE Trans. Emerg. Topics Comput.*, to be published.

[27] Z. Wang, Z. Chen, B. Xia, L. Luo, and J. Zhou, "Cognitive relay networks with energy harvesting and information transfer: Design, analysis, and optimization," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2562–2576, Apr. 2016.

[28] Z. Yang, Z. Ding, P. Fan, and G. K. Karagiannidis, "Outage performance of cognitive relay networks with wireless information and power transfer," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3828–3833, May 2016.

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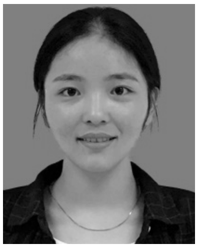

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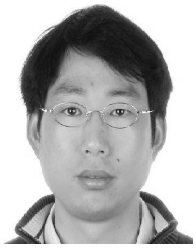

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