Research Article

Bandwidth Allocation of Cognitive Relay Networks with Energy Harvesting for Smart Grid

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In this paper, we investigate an energy harvesting scheme in a smart grid based on the cognitive relay protocol, where a primary transmitter scavenges energy from the nature sources and then employs the harvested energy to forward the primary signal. Depending on the intensity of the energy harvesting from nature, a secondary user dynamically acts as a relay node to assist the primary transmission or does not. When the energy is not enough powerful to support the direct transmission between two primary users, the secondary users share the spectrum by assisting the primary transmission. For the relaying scheme, both amplify-and-forward (AF) and decode-and-forward (DF) protocols are investigated. We analytically obtain the exact transmission rates for both primary and secondary networks and derive the exact expressions of the system outage probabilities for both primary and secondary users in the smart grid. Moreover, we develop the analytically optimal bandwidth allocation strategy to maximize the total sum rate of the proposed scheme. Numerical results are presented to demonstrate the performance gain of the proposed scheme over the nonoptimal scheme.

1. Introduction

Spectral efficiency has attracted much attention in wireless smart grid communications networks due to the increasing demands of wireless services [1]. It has been demonstrated that cognitive radio is a promising way to improve the efficiency of the radio spectrum by allowing spectrum sharing [2–4]. On the contrary, energy efficiency is another aspect worth considering in wireless smart grid systems [5–7]. In order to lower carbon emissions, reducing energy consumption from wireless systems has become more and more important. As a result, combining energy harvesting technology with cognitive radio networks offers a new opportunity to improve both spectral and energy efficiency for the smart grid [8].

In smart grid, harvesting energy from nature such as solar, radio frequency, or wind provides a new free source of energy for the wireless nodes. With nature energy harvesting technique, wireless devices can utilize the free renewable energy sources to improve the energy efficiency [9]. In the field of cognitive networks, the energy harvesting has been developed in [10–14]. In [10], the authors investigated the relationship between the optimal sensing threshold and sensing duration in order to maximize the average throughput of the secondary network in a cognitive radio. Park and Hong [11] applied energy harvesting to the cognitive radio network in which the secondary transmitter harvests energy from ambient sources. The theoretical upper bound on the maximum achievable throughput of secondary transmitter was

derived, which is a function of the temporal correlation of the primary traffic and the energy arrival rate. In [12], a cognitive radio system was considered. Specifically, an energy harvesting secondary user attempts to access the primary channel randomly. The impact of the multi-packet reception capability, the primary queueing delay constraints, and the energy queue arrivals on the maximum secondary throughput was investigated. Park and Hong [13] provided an optimal spectrum sensing policy for an energy harvesting cognitive radio which is in purpose of maximizing the expected total throughput. Besides, an approximate solution to the optimal detection threshold was also presented. Similar researches include two-way channel [15], two-user MIMO interference channels [16], and cognitive radio systems [17–23].

In this paper, considering the massive potential of harvesting energy from nature resources, we adopt this technique to cognitive radio network where we assume the primary user lacks of energy and thus harvests energy from the nature resources. Due to the fluctuation of energy harvesting from nature sources, we model and propose an energy harvesting and relaying protocol with dynamic bandwidth allocation in cognitive relay networks. The protocol enables a secondary user dynamically sharing the primary spectrum by assisting the primary transmission if the direct transmission between two primary users cannot be effectively realized. In particular, the energy harvesting primary user first scavenges energy from ambient sources and then decides to cooperate with the secondary network or transmit information directly to its destination based on the intensity of the harvesting energy. If the direct transmission data rate meets the basic threshold requirement, the direct transmission between two primary users occurs and some bandwidth is allocated to the secondary network. If the direct transmission data rate is below the threshold, the secondary user acts as the relay to assist the primary transmission and the secondary network can share some bandwidth for its own transmission in return. We first derive the analytical expressions of the data rates for the primary and secondary networks. Accordingly, the system outage probabilities for PD and SD are then derived for different transmission schemes. In order to maximize the sum data rate, the optimal bandwidth allocation strategies are analyzed and proposed. Furthermore, the correspondingly analytical policies are derived to solve the optimization problems. Finally, numerical results provide us with the valuable insights into the performance under various system parameters, i.e., the energy arrival rate and the location of the relay.

An outline of the remainder of the paper is as follows. Section 2 describes the system model for the smart grid with the cooperative of cognitive radio technology and discusses the transmission protocol. Section 3 derives the system outage probabilities for PD and SD. Section 4 formulates the optimal bandwidth allocation for maximizing the sum rate and obtains the optimal allocation policy. The numerical results are presented in Section 5, and the conclusions are drawn in Section 6.

2. System Model and Protocol Description

In this section, we begin by describing the smart grid system with the cognitive relay model based on energy harvesting.

2.1. System Model. We consider a cognitive network which is composed of four nodes, as shown in Figure 1. Let us denote the primary source node as “PS,” the primary destination node as “PD,” the secondary source node as “SS,” and the secondary destination node as “SD.” The PS is capable of harvesting energy from nature resources and has a rechargeable battery which is modeled as a queue. E_u is the amount of Joules per energy packet. We assume that PS has an infinite length buffer to store the arrived energy packets which is a reasonable assumption if the packet length is very small compared with the buffer’s size [21].

We suppose that the secondary user SS has a constant power supply, i.e., P , while there is no fixed energy provided for the primary node PS, and it thus requires harvesting energy from the nature resources. We adopt a Rayleigh flat fading channel model, and assume that the channel gains remain constant over the duration of a time slot, T . Besides, the channel state information (CSI) is perfect known by the transmitting terminals PS and SS (we can use a short CSI training phase prior to the transmission to obtain the CSI. For example, PD and SD can estimate the channel gains based on the pilot transmitted from PS and SS in a predetermined sequence and then broadcast their corresponding channel gains to PS and SS. This short CSI training phase overhead is reasonably negligible in an assumed quasi-static fading channel). Let h_1, h_2, h_3 , and h_4 be the channel coefficient between PS and SS, SS and PD, PS and PD, and SS and SD, respectively. We thus have $h_i \sim \mathcal{CN}(0, \Omega_i)$ for $i = 1, 2, 3, 4$. The joint instantaneous channel coefficient is denoted by $\mathbf{h} \triangleq [h_1, h_2, h_3, h_4]$. We also assume that σ_0^2 is the additive white Gaussian (AWGN) noise with power per unit frequency. The spectrum licensed to the primary network is denoted as W .

The time slot T is divided into small intervals, which has a length of δ . We then have $n = T/\delta$ mini slots. Besides, the probability of receiving one energy packet within a mini slot is assumed to be p . Therefore, the number of harvested nature energy packets during one time slot T meets Bernoulli distribution with parameters n and p . If n is large enough and p is small enough, the number of harvested nature energy packets within one time slot T can be approximated as Poisson distribution with a parameter $\lambda_e T = np$, where λ_e is the energy arrival rate. The probability of harvesting i packets from nature resources within one time slot T is expressed as follows:

$$p_I(i) = \frac{(\lambda_e T)^i \exp(-\lambda_e T)}{i!}, \quad i = 0, 1, 2, \dots, n. \quad (1)$$

Accordingly, the mean transmitted power can be expressed as

FIGURE 1: System model of the energy harvesting and relaying protocol for the cognitive relay networks.

$$P_S = \sum_{i=0}^n \frac{iE_u P_I(i)}{T}. \quad (2)$$

$$R = W \log_2 \left(1 + \frac{P_S |h_3|^2}{W \sigma_0^2} \right), \quad (3)$$

2.2. Energy Harvesting and Relaying Protocol. Because of the nature fluctuation, PS sometimes harvests high energy, and sometimes, it harvests low energy from the nature sources. Accordingly, we propose the following energy harvesting and relaying protocol:

- (i) When the harvesting energy is powerful enough to support the direct transmission between two primary nodes, the primary network operates in the direct transmission mode and w_1 spectrum will be allocated to the primary network while the rest to the secondary network. Therefore, the transmission consists of only one phase which lasts for one slot time T .
- (ii) If the data rate of the direct transmission between two primary nodes cannot meet the threshold requirement, the secondary node SS acts as the relay to assist the primary transmission. As return, the primary network allocates some bandwidth to the secondary network for its own transmission and the rest bandwidth w_1 for the primary transmission. Here, we assume that SS always has data to transmit. In this scenario, the transmission operates in two phases. During the first phase, PS exploits all the harvested energy to transmit the information to SS. During the second phase, SS forwards the received signals along with the information intended for SD based on the AF or DF scheme. In this paper, we assume that each phase is $T/2$.

2.2.1. AF Scheme. At the beginning of each time slot, PS ascertains the availability of direct transmission between two primary users, and the test function is given as

where $W \sigma_0^2$ follows the fact that the unit of power P_S is watt, but the unit of σ_0^2 is watt per unit frequency.

If R exceeds the primary data rate threshold R_{th} , then w_1 spectrum is allocated to the primary network and PS sends its information to PD without the assistance of SS. In this scenario, the secondary network has w_2 spectrum for its transmission, where $w_1 + w_2 = W$. Therefore, the data rate for primary and secondary network is given by

$$R_{PD}^{AF} = w_1 \log_2 \left(1 + \frac{P_S |h_3|^2}{w_1 \sigma_0^2} \right), \quad (4)$$

$$R_{SD}^{AF} = w_2 \log_2 \left(1 + \frac{P |h_4|^2}{w_2 \sigma_0^2} \right).$$

If R is below R_{th} , SS acts as the relay to assist the primary transmission. Bandwidth w_1 is allocated to the primary network, while rest bandwidth w_2 is allocated to the secondary network. During the first phase, the primary node PS sends its information to the relay SS. The received signal of SS in frequency band w_1 can thus be formulated as

$$y_{SS} = \sqrt{2P_S} h_1 x_1 + n_1, \quad (5)$$

where x_1 is the unit-power signal intended for PD. $n_1 \sim \mathcal{CN}(0, \sigma_1^2)$ denotes the narrow-band AWGN introduced by the antenna at SS [22]. The coefficient 2 is due to the fact that the time duration of each phase is $T/2$.

During the second phase, SS uses half of its power to broadcast the received primary signals and employs the rest power to transfer signals intended for SD. The information transmitted in frequency band w_1 is given by

$$x_{SS} = \beta \sqrt{\frac{1}{2P}} (y_{SS} + n_{b1}), \quad (6)$$

where $n_{b1} \sim \mathcal{CN}(0, \sigma_{b1}^2)$ denotes AWGN introduced by the signal conversion from passband to baseband at SS, and the coefficient $1/2$ is account of the half power allocated to the primary transmission. The power normalization factor β of the relay SS is

$$\beta = \frac{1}{\sqrt{2P_S|h_1|^2 + w_1(\sigma_1^2 + \sigma_{b1}^2)}} \approx \frac{1}{\sqrt{2P_S|h_1|^2}}, \quad (7)$$

where the approximation is tight at high SNR.

The corresponding received signal at primary user PD in frequency band w_1 can be expressed as

$$\begin{aligned} y_{PD} &= h_2 x_{SS} + n_2 \\ &= \sqrt{P_S} \beta h_1 h_2 x_1 + \sqrt{\frac{1}{2P}} \beta h_2 n_1 \\ &\quad + \sqrt{\frac{1}{2P}} \beta h_2 n_{b1} + n_2, \end{aligned} \quad (8)$$

where $n_2 \sim \mathcal{CN}(0, \sigma_2^2)$ denotes the AWGN at PD.

Accordingly, we the data rates for PD and SD, respectively, as follows:

$$R_{PD}^{AF} = \frac{w_1}{2} \log_2 \left[1 + \frac{2PP_S|h_1|^2|h_2|^2}{P|h_2|^2 w_1(\sigma_{b1}^2 + \sigma_1^2) + 4P_S|h_1|^2 w_1 \sigma_2^2} \right], \quad (9)$$

$$R_{SD}^{AF} = \frac{1}{2} w_2 \log_2 \left(1 + \frac{P|h_4|^2}{2w_2 \sigma_0^2} \right). \quad (10)$$

In fact, the noise introduced by the received antenna is much smaller than that of the baseband noise power. Without loss of generality, we assume the antenna noise power to be zero [23], i.e., $\sigma_1^2 = 0$. Consequently, we have $\sigma_2^2 = \sigma_{b1}^2 = \sigma_0^2$. As a result, we rewrite the data rate of PD as follows:

$$R_{PD}^{AF} = \frac{1}{2} w_1 \log_2 \left[1 + \frac{2PP_S|h_1|^2|h_2|^2}{w_1 \sigma_0^2 (P|h_2|^2 + 4P_S|h_1|^2)} \right]. \quad (11)$$

2.2.2. DF Scheme. If R meets need of the primary rate threshold R_{th} , the data rate for the primary and secondary network are given by

$$R_{PD}^{DF} = w_1 \log_2 \left(1 + \frac{P_S|h_3|^2}{w_1 \sigma_0^2} \right), \quad (12)$$

$$R_{SD}^{DF} = w_2 \log_2 \left(1 + \frac{P|h_4|^2}{w_2 \sigma_0^2} \right),$$

respectively.

If R is below the primary rate threshold, the transmission mechanism is the same with the AF scheme. The data rate achieved at PD and SD can be given by

$$R_{PD}^{DF} = \min\{R_1, R_2\}, \quad (13)$$

$$R_{SD}^{DF} = \frac{1}{2} w_2 \log_2 \left(1 + \frac{P|h_4|^2}{2w_2 \sigma_0^2} \right), \quad (14)$$

where $R_1 = (1/2)w_1 \log_2(1 + ((2P_S|h_1|^2)/(w_1 \sigma_0^2)))$ denotes the rate from PS to SS in the first phase and $R_2 = (1/2)w_1 \log_2(1 + ((P|h_2|^2)/(2w_1 \sigma_0^2)))$ denotes the rate from SS to PD in the second phase.

3. System Outage Probability Analysis

In this section, we investigate the system outage performance in Rayleigh fading environments. If the transmission rates of PD or SD is lower than the given target rate, the system occurs an outage event. Therefore, we have the following proposition for the primary user PD.

Proposition 1. Let $a_1 = (w_1 \sigma_0^2)/(2P_S)$, $b_1 = (2w_1 \sigma_0^2)/P$, and $c_1 = 1/(2^{2R_{th}/w_1} - 1)$. Given a target rate R_{th} , the system outage probability for the primary user PD with the AF scheme can be expressed as

$$\begin{aligned} \mathcal{P}_{out}^{PD,AF} &= \left(1 - \exp \left(\frac{-(2^{R_{th}/W} - 1)W\sigma_0^2}{P_S \Omega_3} \right) \right) \\ &\quad \cdot \left(1 - \int_0^{c_1/b_1} \frac{1}{y^2 \Omega_2} \exp \left(\frac{-1}{y \Omega_2} \right) \right. \\ &\quad \cdot \exp \left(\frac{-a_1}{\Omega_1 (c_1 - b_1 y)} \right) dy \Bigg) \\ &\quad + \exp \left(\frac{-(2^{R_{th}/W} - 1)W\sigma_0^2}{P_S \Omega_3} \right) \\ &\quad \cdot \left(1 - \exp \left(\frac{-(2^{R_{th}/w_1} - 1)w_1 \sigma_0^2}{P_S \Omega_3} \right) \right). \end{aligned} \quad (15)$$

And for the DF scheme, we have

$$\begin{aligned} \mathcal{P}_{out}^{PD,DF} &= \exp \left(\frac{-(2^{R_{th}/W} - 1)W\sigma_0^2}{P_S \Omega_3} \right) \\ &\quad \cdot \left(1 - \exp \left(\frac{-(2^{R_{th}/w_1} - 1)w_1 \sigma_0^2}{P_S \Omega_3} \right) \right) \\ &\quad + \left(1 - \exp \left(\frac{-(2^{R_{th}/W} - 1)W\sigma_0^2}{P_S \Omega_3} \right) \right) \\ &\quad \cdot \left(1 - \exp \left(\frac{-a_1}{c_1 \Omega_1} \right) \exp \left(\frac{-b_1}{c_1 \Omega_2} \right) \right). \end{aligned} \quad (16)$$

Proof. Accordingly, we have the outage probability

$$\mathcal{P}_{\text{out}}^{\text{PD,AF}} = \Pr(R_{\text{PD}}^{\text{AF}} < R_{\text{th}}) = \Pr(R_{\text{PD}}^{\text{AF}} < R_{\text{th}} \mid R \leq R_{\text{th}}) + \Pr(R_{\text{PD}}^{\text{AF}} < R_{\text{th}} \mid R > R_{\text{th}}), \quad (17)$$

$$\begin{aligned} \mathcal{P}_{\text{out}}^{\text{PD,AF}} &= \Pr\left(W \log_2 \left(1 + \frac{P_S |h_3|^2}{W \sigma_0^2}\right) \leq R_{\text{th}}\right) \\ &\cdot \Pr\left(\frac{1}{2} w_1 \log_2 \left[1 + \frac{2PP_S |h_1|^2 |h_2|^2}{w_1 \sigma_0^2 (P|h_2|^2 + 4P_S |h_1|^2)}\right] \right. \\ &< R_{\text{th}} \Bigg) + \Pr\left(W \log_2 \left(1 + \frac{P_S |h_3|^2}{W \sigma_0^2}\right) > R_{\text{th}}\right) \\ &\cdot \Pr\left(w_1 \log_2 \left(1 + \frac{P_S |h_3|^2}{w_1 \sigma_0^2}\right) < R_{\text{th}}\right). \end{aligned} \quad (18)$$

Let $X = 1/|h_1|^2$ and $Y = 1/|h_2|^2$, where the corresponding probability density function (PDF) can be presented as

$$\begin{aligned} \Pr_X(x) &= \frac{1}{\Omega_1 x^2} \exp\left(\frac{-1}{\Omega_1 x}\right), \\ \Pr_Y(y) &= \frac{1}{\Omega_2 y^2} \exp\left(\frac{-1}{\Omega_2 y}\right). \end{aligned} \quad (19)$$

Therefore, we have

$$\begin{aligned} &\Pr\left(\frac{1}{2} w_1 \log_2 \left[1 + \frac{2PP_S |h_1|^2 |h_2|^2}{w_1 \sigma_0^2 (P|h_2|^2 + 4P_S |h_1|^2)}\right] < R_{\text{th}}\right) \\ &= \Pr(a_1 X + b_1 Y > c_1) \\ &= 1 - \int_0^{c_1/b_1} \int_0^{(c_1 - b_1 y)/a_1} \Pr_X(x) \Pr_Y(y) dx dy \\ &= 1 - \int_0^{c_1/b_1} \frac{1}{y^2 \Omega_2} \exp\left(\frac{-1}{y \Omega_2}\right) \exp\left(\frac{-a_1}{\Omega_1 (c_1 - b_1 y)}\right) dy. \end{aligned} \quad (20)$$

Based on (17) and (20), we can easily to obtain the proposition.

Similarly, the system outage probability for the secondary user SD is given by the following proposition.

Proposition 2. For both the AF and DF scheme, the system outage probability for the secondary user SD is

$$\begin{aligned} \mathcal{P}_{\text{out}}^{\text{SD}} &= \exp\left(\frac{-(2^{R_{\text{th}}/W} - 1)W \sigma_0^2}{P_S \Omega_3}\right) \left(1 - \exp\left(\frac{-(2^{R_{\text{th}}/w_2} - 1)w_2 \sigma_0^2}{P \Omega_4}\right)\right) \\ &+ \left(1 - \exp\left(\frac{-(2^{R_{\text{th}}/W} - 1)W \sigma_0^2}{P_S \Omega_3}\right)\right) \\ &\left(1 - \exp\left(\frac{-(2^{2R_{\text{th}}/w_2} - 1)2w_2 \sigma_0^2}{P \Omega_4}\right)\right). \end{aligned} \quad (21)$$

Proof. Similar to the proof of Proposition 1, we can have this proposition. $\square$

4. Optimization Problem: Sum Data Rate

In this section, we attempt to maximize the sum rate of the whole system for both the AF and DF scheme. However, this depends on the value of R . If R exceeds the data threshold, then the exact value is given by (4) and (12). If R is below the threshold, the primary network will allocate some bandwidth to the secondary network for its own transmission. The data rate in (10), (11), (13), and (14) depends on bandwidth distribution.

4.1. AF Scheme. The Optimization Problem 1 (OP1) for the AF scheme can be formulated as

$$\begin{aligned} \text{(OP1):} \quad &\max_{w_1(\mathbf{h}, \lambda_e), w_2(\mathbf{h}, \lambda_e)} R_{\text{PD}}^{\text{AF}} + R_{\text{SD}}^{\text{AF}}, \\ &\text{s.t.} \quad (1) w_1(\mathbf{h}, \lambda_e) + w_2(\mathbf{h}, \lambda_e) = W, \\ &\quad (2) 0 \leq w_1(\mathbf{h}, \lambda_e), w_2(\mathbf{h}, \lambda_e) \leq W, \\ &\quad (3) R_{\text{PD}}^{\text{AF}} \geq R_{\text{th}}, \end{aligned} \quad (22)$$

where we use $w_1(\mathbf{h}, \lambda_e)$ and $w_2(\mathbf{h}, \lambda_e)$ to replace w_1 and w_2 since w_1 and w_2 are in dynamic adjustment in correspondence with the instantaneous channel coefficients and energy arrival rate.

In order to simplify the expression of $R_{\text{PD}}^{\text{AF}}$ and $R_{\text{SD}}^{\text{AF}}$, we rewrite $R_{\text{PD}}^{\text{AF}} + R_{\text{SD}}^{\text{AF}}$ as follows:

$$\left\{ \begin{aligned} &\frac{w_1(\mathbf{h}, \lambda_e)}{2} \log_2 \left(1 + \frac{\varphi_1}{w_1(\mathbf{h}, \lambda_e)}\right) \\ &+ \frac{w_2(\mathbf{h}, \lambda_e)}{2} \log_2 \left(1 + \frac{\nu_1}{w_2(\mathbf{h}, \lambda_e)}\right), \quad R \leq R_{\text{th}}, \\ &w_1(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{\varphi_3}{w_1(\mathbf{h}, \lambda_e)}\right) \\ &+ w_2(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{2\nu_1}{w_2(\mathbf{h}, \lambda_e)}\right), \quad R > R_{\text{th}}. \end{aligned} \right. \quad (23)$$

where φ_1 , φ_3 , and ν_1 are given in Table 1.

- (1) $R \leq R_{\text{th}}$: first, we do not consider the restricted condition of $R_{\text{PD}}^{\text{AF}} \geq R_{\text{th}}$. Then, we use $G_i(w_i(\mathbf{h}, \lambda_e))$ to represent the data rate of each network user, where $G_i(w_i(\mathbf{h}, \lambda_e)) \triangleq (1/2)w_i(\mathbf{h}, \lambda_e) \log_2(1 + m_i/w_i(\mathbf{h}, \lambda_e))$ is a concave and increasing function of $w_i(\mathbf{h}, \lambda_e)$ and m_i is a constant, i.e., $m_1 = \varphi_1$ and $m_2 = \nu_1$, $i = 1, 2$. The first part of (23) resembles the classical water-filling power distribution problem [24]. As a result, we obtain the requirement for the optimal solution of the problem, denoted by $w_{i\text{AF}}^{\text{fb}}(\mathbf{h}, \lambda_e)$:

TABLE 1: Symbol notations.

Symbol	Notation
φ_1	$(2PP_S h_1 ^2 h_2 ^2)/((P h_2 ^2 + 4P_S h_1 ^2)\sigma_0^2)$
φ_2	$(P h_2 ^2)/(2\sigma_0^2)$
φ_3	$(P_S h_3 ^2)/\sigma_0^2$
ν_1	$(P h_4 ^2)/(2\sigma_0^2)$
ν_2	$(2P_S h_1 ^2)/\sigma_0^2$

$$\left. \frac{\partial G_1(w_1(\mathbf{h}, \lambda_e))}{\partial w_1(\mathbf{h}, \lambda_e)} \right|_{w_1(\mathbf{h}, \lambda_e) = w_{1AF}^{tb}(\mathbf{h}, \lambda_e)} \quad (24)$$

$$= \left. \frac{\partial G_2(w_2(\mathbf{h}, \lambda_e))}{\partial w_2(\mathbf{h}, \lambda_e)} \right|_{w_2(\mathbf{h}, \lambda_e) = w_{2AF}^{tb}(\mathbf{h}, \lambda_e)},$$

and we have

$$\left. \frac{\partial G_i(w_i(\mathbf{h}, \lambda_e))}{\partial w_i(\mathbf{h}, \lambda_e)} \right|_{w_i(\mathbf{h}, \lambda_e) = w_{iAF}^{tb}(\mathbf{h}, \lambda_e)}$$

$$= \frac{1}{2} \left[\log_2 \left(1 + \frac{m_i}{w_{iAF}^{tb}(\mathbf{h}, \lambda_e)} \right) - \frac{m_i}{\ln_2(w_{iAF}^{tb}(\mathbf{h}, \lambda_e) + m_i)} \right]$$

$$= Y \left(\frac{m_i}{w_{iAF}^{tb}(\mathbf{h}, \lambda_e)} \right), \quad (25)$$

where the function $Y(x) \triangleq 1/2 \log_2(1+x) - x/[2 \ln_2(1+x)]$ is monotonically increasing. From (24), we obtain that

$$\frac{m_1}{w_{1AF}^{tb}(\mathbf{h}, \lambda_e)} = \frac{m_2}{w_{2AF}^{tb}(\mathbf{h}, \lambda_e)}, \quad (26)$$

as $w_{1AF}^{tb}(\mathbf{h}, \lambda_e) + w_{2AF}^{tb}(\mathbf{h}, \lambda_e) = W$. Furthermore, from (26), we have the optimal solution for bandwidth allocation:

$$w_{1AF}^{tb}(\mathbf{h}, \lambda_e) = \frac{m_1 W}{m_1 + m_2}$$

$$= \frac{4P_S W |h_1|^2 |h_2|^2}{(P|h_2|^2 + 4P_S|h_1|^2)|h_4|^2 + 4P_S|h_1|^2|h_2|^2}, \quad (27)$$

where, we take the restricted condition of $R_{PD}^{AF} \geq R_{th}$ into consideration. $G_1(w_1(\mathbf{h}, \lambda_e))$ must exceed the threshold R_{th} , so we suppose that $w_{1AF}^{tb}(\mathbf{h}, \lambda_e)$ is the solution to $G_1(w_1(\mathbf{h}, \lambda_e)) = R_{th}$. Since $G_1(w_1(\mathbf{h}, \lambda_e))$ is increasing in $w_1(\mathbf{h}, \lambda_e)$, the optimal $w_{1AF}^{tb}(\mathbf{h}, \lambda_e)$ must exceed $w_{1AF}^{tb}(\mathbf{h}, \lambda_e)$. As a result, we obtain the optimal bandwidth for the primary network:

$$w_{1AF}^{*b}(\mathbf{h}, \lambda_e) = \max\{w_{1AF}^{tb}(\mathbf{h}, \lambda_e), w_{1AF}^{tb}(\mathbf{h}, \lambda_e)\}. \quad (28)$$

(2) $R > R_{th}$: similar to the situation of $R \leq R_{th}$, we have the optimal bandwidth for the primary network:

$$w_{1AF}^{*o}(\mathbf{h}, \lambda_e) = \max\{w_{1AF}^{to}(\mathbf{h}, \lambda_e), w_{1AF}^{*b}(\mathbf{h}, \lambda_e)\}, \quad (29)$$

where

$$w_{1AF}^{to}(\mathbf{h}, \lambda_e) = \frac{\varphi_3 W}{\varphi_3 + 2\nu_1} = \frac{P_S W |h_3|^2}{P_S |h_3|^2 + P |h_4|^2}, \quad (30)$$

$w_{1AF}^{*o}(\mathbf{h}, \lambda_e)$ is the solution to $w_1(\mathbf{h}, \lambda_e) \log_2(1 + \varphi_3/w_1(\mathbf{h}, \lambda_e)) = R_{th}$.

4.2. DF Scheme. The Optimization Problem 2 (OP2) for the DF scheme can be formulated as

$$(OP2): \quad \max_{w_1(\mathbf{h}, \lambda_e), w_2(\mathbf{h}, \lambda_e)} \quad R_{PD}^{DF} + R_{SD}^{DF},$$

$$\text{s.t.} \quad (1) \quad w_1(\mathbf{h}, \lambda_e) + w_2(\mathbf{h}, \lambda_e) = W,$$

$$(2) \quad 0 \leq w_1(\mathbf{h}, \lambda_e), w_2(\mathbf{h}, \lambda_e) \leq W,$$

$$(3) \quad R_{PD}^{DF} \geq R_{th}. \quad (31)$$

For the sake of simplicity, we rewrite $R_{PD}^{DF} + R_{SD}^{DF}$ as follows:

$$\left\{ \begin{array}{ll} \min\{R_1, R_2\} + \frac{1}{2} w_2(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{\nu_1}{w_2(\mathbf{h}, \lambda_e)} \right), & R \leq R_{th}, \\ w_1(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{\varphi_3}{w_1(\mathbf{h}, \lambda_e)} \right) \\ + w_2(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{2\nu_1}{w_2(\mathbf{h}, \lambda_e)} \right), & R > R_{th}, \end{array} \right. \quad (32)$$

where

$$R_1 = \frac{1}{2} w_1(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{\nu_2}{w_1(\mathbf{h}, \lambda_e)} \right), \quad (33)$$

$$R_2 = \frac{1}{2} w_1(\mathbf{h}, \lambda_e) \log_2 \left(1 + \frac{\varphi_2}{w_1(\mathbf{h}, \lambda_e)} \right),$$

where φ_2 and ν_2 are given in Table 1.

(1) $R \leq R_{th}$: similar to the AF scheme, we obtain the optimal bandwidth allocation policy for the primary network user:

$$w_{1DF}^{*b}(\mathbf{h}, \lambda_e) = \max\{w_{1DF}^{tb}(\mathbf{h}, \lambda_e), w_{1DF}^{*b}(\mathbf{h}, \lambda_e)\}, \quad (34)$$

where

$$w_{1DF}^{tb}(\mathbf{h}, \lambda_e) = \min\{w_{1DF}^{tb}(\mathbf{h}, \lambda_e), w_{1DF}^{*b}(\mathbf{h}, \lambda_e)\},$$

$$w_{1DF}^{*b}(\mathbf{h}, \lambda_e) = \frac{\nu_2}{\nu_2 + \nu_1} = \frac{4P_S |h_1|^2}{4P_S |h_1|^2 + P |h_4|^2}, \quad (35)$$

$$w_{1DF}^{*b}(\mathbf{h}, \lambda_e) = \frac{\varphi_2}{\varphi_2 + \nu_1} = \frac{|h_2|^2}{|h_2|^2 + |h_4|^2},$$

$w_{1DF}^{*b}(\mathbf{h}, \lambda_e)$ is the solution to $\min\{R_1, R_2\} = R_{th}$.

(2) $R > R_{th}$: the optimal bandwidth allocation solution is the same as the AF scheme:

$$w_{1DF}^{*o}(\mathbf{h}, \lambda_e) = \max\{w_{1DF}^{\dagger o}(\mathbf{h}, \lambda_e), w_{1DF}^{\ddagger o}(\mathbf{h}, \lambda_e)\}, \quad (36)$$

where

$$w_{1DF}^{\dagger o}(\mathbf{h}, \lambda_e) = \frac{P_S W |h_3|^2}{P_S |h_3|^2 + P |h_4|^2}, \quad (37)$$

$w_{1DF}^{\ddagger o}(\mathbf{h}, \lambda_e)$ is the solution to $w_1(\mathbf{h}, \lambda_e) \log_2(1 + \varphi_3/w_1(\mathbf{h}, \lambda_e)) = R_{th}$.

5. Numerical Results

In this section, we present some numerical results to verify the effectiveness of the proposed protocol and the analytical optimization solutions. Besides, the derived analytical results are employed to provide insights into the different parameter's impact on the whole system. In the simulation, the distance between PS and PD is normalized. Let d_1 , d_2 , d_3 , and d_4 denote the distance between PS and SS, SS and PD, PS and PD, and SS and SD, respectively. Considering the large-scale fluctuation, we have $\Omega_1 = 1/d_1^3$, $\Omega_2 = 1/d_2^3$, $\Omega_3 = 1/d_3^3$, and $\Omega_4 = 1/d_4^3$ for h_1 , h_2 , h_3 , and h_4 , respectively. The parameters used to generate the figure are $T = 1$ ms, $E_u = 0.006$ J, $W = 20$ kHz, $n = 20$, and $\sigma_0^2 = 10^{-6}$ W/Hz.

In Figure 2, the analytical results for system outage probability are evaluated. For either PD and SD, the analytical expressions are given in (15), (16), and (21). We observe that the system outage probability of PD with the AF scheme is very close to that of the DF scheme. Also, we find that SD can achieve a better outage probability than PD.

In Figure 3, the analytical results for optimized sum rates of the AF and DF scheme are examined and verified through simulation under different distance d_1 . For either AF or DF scheme, the analytical optimization solutions are given in (28), (29), (34), and (36). To test the optimized results, we present one pair of AF and DF results with fixed bandwidth allocation, i.e., $w_1/W = 1/2$. We notice from Figure 3 that the optimized sum data rates achieve evident improvement compared with fixed bandwidth allocation. For the AF scheme, the sum rate first increases with increase of d_1 and then decreases with increase of d_1 , and it achieves maximum when $d_1 = 0.85$. While for the DF scheme, the situation is inverse. This can be explained as following: for the AF scheme, the harvested energy of PS is impotent compared with SS's transmitted power. As a result, the SS's power become dominating which generates the situation where the distance between SS and PD has a vital influence on the sum rate. When d_1 increases, the distance between SS and PD decreases, which leads to less path loss and more sum rate. When d_1 is too large, PS and SS cannot communicate effectively which leads to reduction of the sum data rate. For the DF scheme, the PS's power is dominating and the distance between PS and SS has a major influence on the sum rate. Therefore, with increase of d_1 , the pass loss between PS and SS increases which results in less sum rate. Moreover, when d_1 is below approximate 0.5, DF scheme outperforms

FIGURE 2: System outage probability vs. $P_S/W\sigma_0^2$ ($d_4 = 1/2$, $R_{th} = 10000$ bps, and $P = 0.0632$ W).

FIGURE 3: Sum data rate vs. distance d_1 ($d_4 = 1/2$, $\lambda_e = 2$ packets/s, $R_{th}/W = 1/2$ bps/Hz, and $P = 1$ W).

the AF scheme. The situation is opposite when d_1 exceeds 0.5.

In Figure 4, we present numerical examples of sum data rates under different energy arrival rates. Compared with fixed w_1/W , the optimized results are extremely improved. Besides, Figure 4 shows that the sum data rates of the AF and DF scheme increase as the energy arrival rate increases. This is due to the fact that large energy arrival rate leads to more energy allocated to data transmission which increases the sum data rates. Furthermore, compared with direct transmission, we find that the proposed protocol can achieve a better transmission data rate of the primary user. Figure 5

FIGURE 4: Sum data rate vs. energy arrival rate λ_e ($d_1 = 1/3$, $d_4 = 1/2$, $R_{th}/W = 1/2$ bps/Hz, and $P = 1$ W).

FIGURE 5: Sum data rate vs. the relay's power P ($d_1 = 1/3$, $d_4 = 1/2$, $\lambda_e = 2$ packets/s, and $R_{th}/W = 1/2$ bps/Hz).

depicts the impact of P on the performance of sum data rates. We firstly observe that the optimized results are conspicuously enhanced. Besides, Figure 5 illustrates that, with increase of P , the sum rate for either case increases, which can be interpreted by its physical meaning. Larger P means that more power is employed to assist the primary and secondary transmission which boosts the sum data rate. Moreover, the DF scheme outperforms the AF scheme which is on account of specific d_1 .

In Figure 6, we evaluate the impact of λ_e on the optimal w_1 . It is interesting to note that w_1/W decreases when λ_e increases. This is because when λ_e is small, more bandwidth is allocated to the primary network in order to meet the threshold requirement, thus resulting in large w_1/W . We also note that when λ_e increases, the difference of w_1/W

FIGURE 6: Bandwidth allocation vs. energy arrival rate λ_e ($d_1 = 1/3$, $d_4 = 1/2$, and $P = 1$ W).

between AF and DF scheme shrinks. This can be explained as follows: when λ_e is large, more energy is harvested to assist the primary transmission, which tends to do direct transmission. As result, the gap between AF and DF decreases. Besides, when λ_e is large enough, the curve of the DF scheme changes smoothly. This is due to the fact that, for large λ_e , the primary data rate is more likely determined by the rate between SS and PD, which is a constant value. Therefore, w_1/W varies slowly when λ_e increases in the large range of values. Moreover, compared with the DF scheme, w_1/W is larger under the AF scheme. This is because for the AF scheme, the secondary signals interfere with the primary transmission which leads more bandwidth distributed to the primary network so as to meet the threshold requirement. Furthermore, for each scheme, w_1/W under $R_{th}/W = 1$ bps/Hz is larger than the situation under $R_{th}/W = 1/2$ bps/Hz. This is on account of the reason that larger R_{th} means more threshold requirement for the primary transmission which leads to more bandwidth allocated to the primary network.

6. Conclusion

In this paper, we have investigated an energy harvesting and relaying protocol in the smart grid with cognitive relay networks. The proposed protocol enables the secondary network opportunistically share the spectrum licensed to the primary network by assisting the primary transmission if the direct transmission between two primary users cannot meet the threshold requirement. The exact expressions of data rate for both primary and secondary networks are derived under different relaying schemes, namely, AF and DF schemes. We then derive the system outage probability of PD and SD for both two transmission schemes. Furthermore, in order to improve the performance of whole system, we formulate optimization problems which are in purpose of achieving the maximum sum data rates. For each scheme, we derive the

correspondingly analytical solution. Subsequently, the numerical results verify the accuracy of theoretical derivations. Besides, simulation results demonstrate that the proposed spectrum sharing with energy harvesting in this protocol can achieve better transmission rate compared with the direct transmission. Finally, the numerical results provide us with valuable insights into the influence of various system parameters on the system performance.

Data Availability

The numerical results are directly calculated from the mathematical derivations we provide in this paper. All data are reliable and valid.

Disclosure

The work was partly presented in IEEE/CIC ICC 2016 [25].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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