Joint Resource Allocation for Wireless Energy Harvesting Based on DF Relaying

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Abstract. In this paper, a spectrum sharing protocol of cognitive radio (CR) based on joint resource allocation is proposed. The problem of spectrum access for one-way relaying *CR* networks using decode-and-forward (DF) relaying protocols is investigated. Specifically, in the first phase, the primary transmitter (*PT*) sends its own signal to primary receiver (*PR*) and cognitive transmitter (*CT*). Then, *CT* divides the received signal into two portions, which are used to decode information and harvest energy, respectively. In the second phase, the accessed bandwidth of *CT* is divided into two parts. One of the bandwidth is used to forward $PT's$ signal to *PR* with the harvested energy. *CT* can use the other of bandwidth to send $CT's$ signal to the cognitive receiver (*CR*) by using its own energy. The main object is to maximize cognitive system transmission rate by jointly optimizing the power splitting ratio and bandwidth allocation while satisfying the constraint of primary transmission rate.

Keywords: Energy harvesting · Power splitting · Bandwidth allocation
Spectrum access

1 Introduction

Since wireless communication facilitates people's communication, they want to have higher transmission rate of wireless communication. In order to meet people's needs, we need higher transmission rates, that is, we need more spectrum resources. However, the spectrum resource in nature is limited, and existing fixed spectrum allocation has more or less wastes in time and space, which restricts the development of wireless communications. Cognitive radio (CR) can advance the efficiency of spectrum utilizing by admitting cognitive system to access the licensed spectrum of the primary system while persevering in the interference restriction of the primary systems [1].

With the advantages of expanding coverage of the system and improving reliability of the link, cooperative diversity technology has wide applications in the spectrum access of cognitive radio [2–4]. In distributed spectrum sharing protocols with cooperative relay, the cognitive transmitter uses a part of its power to transmit the primary signal. As a reward, it can transmit its own signal to cognitive receiver by using the remainder [5–7]. In the spectrum access protocol, the cognitive transmitter plays the role of relay, to help reach the target rate of primary system with a part of sub-carriers to transmit the primary signal, while the rest are used for transmitting its signal [8–10].

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Simultaneous wireless information and power transfer (SWIPT) [11] is the product of wireless energy transmission combined with wireless information transmission, which can realize the parallel transmission of information and energy. A relay can harvest energy from the received signal,and forward the received signal to the destination [12, 13]. By optimizing some practical parameters in [14], SWIPT proposes a general framework to maximize network performance. A cooperative SWIPT scheme based on time switching (TS) protocol was presented to maximize the energy-delivery efficiency in wireless sensor networks (WSNs) with multiple nodes [15]. However, there are some flaws in the articles above. Such as, the cognitive user utilizes the same bandwidth to send signal of the primary and cognitive users, which will result in grave interference between the primary and cognitive system.

A spectrum sharing protocol of cognitive radio based on DF relaying is proposed in this paper. Specifically, the accessed bandwidth of cognitive system is divided into two parts. One part is used to send primary signal with the harvested energy, and the other part is used to transmit its own signal by using its own energy. Therefore, independent bandwidth is used to send primary and cognitive signal without interference. We study the joint power splitting ratio and bandwidth allocation optimization to obtain the maximum value of cognitive system transmission rate under the constraint of primary target rate R_T. The simulation results show that the primary and cognitive performance is improved.

The remaining part of this paper is arranged as follows. In Sect. 2, we introduce the components of the system model and the definition of various parameters. In Sect. 3, we propose the formulation and solution of the problem. In Sect. 4, Simulation results explain the performance of the proposed spectrum sharing protocol and power allocation algorithm. Finally, in Sect. 5, we give the conclusion of this paper.

2 System Model

We consider a cognitive radio system make up a primary system and a cognitive system, which is shown in Fig. 1. The primary system is composed of a primary transmitter (*PT*) and a primary receiver (*PR*) which supports the relaying functionality and operates on a licensed spectrum W. The cognitive system is made up of a cognitive transmitter (*CT*) and a cognitive receiver (*CR*), which transmits signal by looking for the chance to get the licensed spectrum. *CT* has the function of energy harvesting, which will acquire and store the energy from the received signal.

We assume that the channel in this system is Rayleigh flat fading channel, h_1, h_2, h_3 and h_4 denote the channel coefficients of the links $PT \rightarrow PR$, $PT \rightarrow CT$, $CT \rightarrow PR$ and $CT \rightarrow CR$, respectively. d_1, d_2, d_3 and d_4 denote the distance of the links $PT \rightarrow PR$, $PT \rightarrow CT$, $CT \rightarrow PR$ and $CT \rightarrow CR$, respectively. We have $h_i \sim CN(0, d_i^{-v})$, $i = 1, 2, 3, 4$, where v is the path loss exponent. $\gamma_i = \left|h_{i,k}\right|^2$ denotes the instantaneous channel gain of h_i. We also assume that all the channel coefficients are constant throughout the whole process. Generally, we assume that all the noise terms are additive white Gaussian noise with a mean of zero and a variance of σ^2.

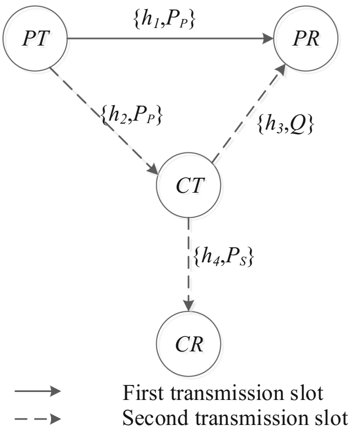

Fig. 1. System model.

We separate the transport process of the system into two phases. firstly, *PT* sends signal to *PR* and *CR* by using its power P_p. *CT* uses one of the received signal to decode information and the other to harvest energy. Secondly, *CT* forward the receives signal to *PR*. As a reward, *CT* can send its own signal to *CR* with the remaining bandwidth by using its transmit power P_c.

3 The Problem Formulation and Solution

Firstly, we consider that there is no cognitive system access, *PT* sends its signal to *PR* directly. The achievable rate of *PR* can be written as

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

When the primary rate R_D falls below the target rate R_T, *PR* will seek cooperation with surrounding cognitive users to help transmit the primary signal.

In the first phase, *PT* transmits its signal to *PR* and *CT*. *CT* uses $\alpha (0 < \alpha < 1)$ fraction of the primary power for decoding information and utilizes the remainder for harvesting energy. Therefore, the rates of $PT \rightarrow PR$ and $PT \rightarrow CT$ links can be expressed as

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

$$R_{\mathrm{p}}^1 = \frac{1}{2}W\log_2(1 + \frac{\alpha\gamma_2 P_P}{\sigma^2}) \tag{3}$$

The energy collected by CT can be expressed as

$$Q = \varepsilon(1-\alpha)\gamma_2 P_P \tag{4}$$

where ε is a constant representing the loss factor for converting energy into electricity.

In the second phase, CT utilizes a part of the bandwidth $bW(0 < b < 1)$ to transmit $PT's$ signal with the collected energy Q. If CT decodes successfully, the primary rate can be expressed as

$$R_p^2 = \frac{1}{2} bW \log_2\left(1 + \frac{\varepsilon(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2} + \frac{P_P\gamma_1}{\sigma^2}\right) + \frac{1}{2}(1-b)W \log_2\left(1 + \frac{P_P\gamma_1}{\sigma^2}\right) \tag{5}$$

After two phases, the achievable rate of PR can be expressed as

$$R_P = \min\{R_p^1, R_p^2\} \tag{6}$$

Meanwhile, CT sends its own signal to CR with the remained bandwidth $(1-b)W$ and cognitive power. Therefore, the rate of CR can be expressed as

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

3.1 Problem Formulation

With the objective of maximize the cognitive rate R_c by joint optimization of power α and bandwidth b while ensuring the primary rate R_P can achieve the target rate R_T. The optimization problem can be written as:

$$\max_{\alpha,b} R_c = \frac{1}{2}(1-b)W \log_2\left(1 + \frac{\gamma_4 P_c}{\sigma^2}\right) \tag{8}$$

$$\text{s.t.} \begin{cases} R_p \geq R_T \\ 0 < \alpha < 1 \\ 0 < b < 1 \end{cases} \tag{9}$$

3.2 Problem Solution

Substituting (3), (5), (6) into the first condition of (9), we can obtain

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

$$\frac{1}{2} bW \log_2\left(1 + \frac{\varepsilon(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2} + \frac{P_P\gamma_1}{\sigma^2}\right) + \frac{1}{2}(1-b)W \log_2\left(1 + \frac{P_P\gamma_1}{\sigma^2}\right) \geq R_T \tag{11}$$

Convert the format (10) and (11), we can obtain

$$\begin{cases} \alpha \geq \frac{\sigma^2 M}{\gamma_2 P_P} \\ b \geq \frac{2R_T - W\log_2(1+\frac{P_P\gamma_1}{\sigma^2})}{W\log_2(1+\frac{\varepsilon(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2+P_P\gamma_1})} \end{cases} \tag{12}$$

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

We have the constraint of $0 < b < 1$, and can obtain

$$\alpha \leq 1 - \frac{\sigma^2 M - \gamma_1 P_P}{\varepsilon\gamma_2\gamma_3 P_P} \tag{13}$$

$$\frac{1}{2} W \log_2\left(1 + \frac{\gamma_1 P_p}{\sigma^2}\right) < R_T \tag{14}$$

In (12) and (7), we can know that b monotonically increases with α and R_c monotonically decreases of b, respectively. Therefore, the joint optimization problem of power α and bandwidth b can be expressed as

$$b^* = \frac{2R_T - W\log_2(1+\frac{P_P\gamma_1}{\sigma^2})}{W\log_2(1+\frac{\varepsilon(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2+P_P\gamma_1})} \tag{15}$$

$$\alpha^* = \frac{\sigma^2 M}{\gamma_2 P_P} \tag{16}$$

Substituting α^* into (15), the optimal b^* can be expressed as

$$b^* = \frac{2R_T - W\log_2(1+\frac{P_P\gamma_1}{\sigma^2})}{W\log_2(1+\frac{\gamma_3\varepsilon(P_P\gamma_2-\sigma^2 M)}{\sigma^2+P_P\gamma_1})} \tag{17}$$

4 Simulation Results

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

Figure 2 presents the value of R_p and R_C versus d_2 in a transmission process. In Fig. 2, we can find that $R_p = R_T, R_C > 0$ when CT moves in the access domain of $[0, 0.595]$. We can also find that when CT moves in the access domain of $[0.596, 1]$, $R_p = R_D, R_C = 0$, which indicates that CT can't operate on the primary spectrum. This is because that when $CT's$ location is aloof from PT, the SNR of $PT \to CT$ link is worse and then the harvested energy Q at CT will be less and less. It will lead to CT can't help the value of R_p to reach the target rate R_T. Hence, the cognitive system will not be admitted to operate on the spectrum of primary system.

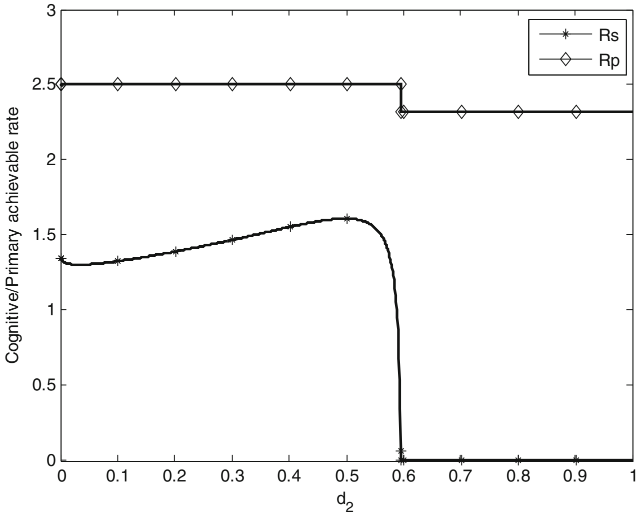

Fig. 2. Value of R_P and R_c versus d_2.

Figure 3 presents the value of R_C versus P_c with different R_T when CT in the access domain. From Fig. 3, we can observe that the rate of the cognitive system increases with the increase of the cognitive transmit power P_c, which is because CT only uses P_c to send cognitive signal in the access domain. Figure 4 presents the value of R_C versus d_2 with different R_T. From Fig. 4, we can observe that when CT is not in access domain, the rate of the cognitive system increases first, and then decreases as d_2 increase. When CT is not in access domain, the rate of the cognitive system would become zero. It is because that the SNR of $PT \to CT$ link is worse when $CT's$ location is too close or too far away from PT. We can also discover from the following figures that the cognitive rate R_C will decrease as the target rate R_T increase. It is because that when R_T gets larger, CT will use more bandwidth to transmit $PT's$ signal to reach the target rate R_T, which leads to less bandwidth being left to send its own signal.

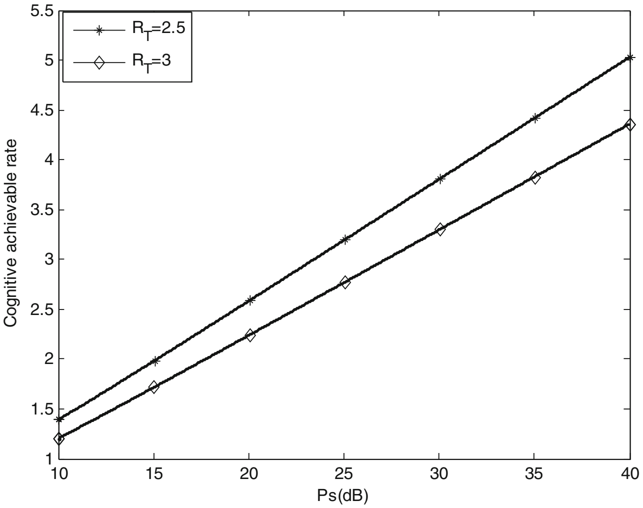

Fig. 3. Value of R_c versus P_c with different R_T

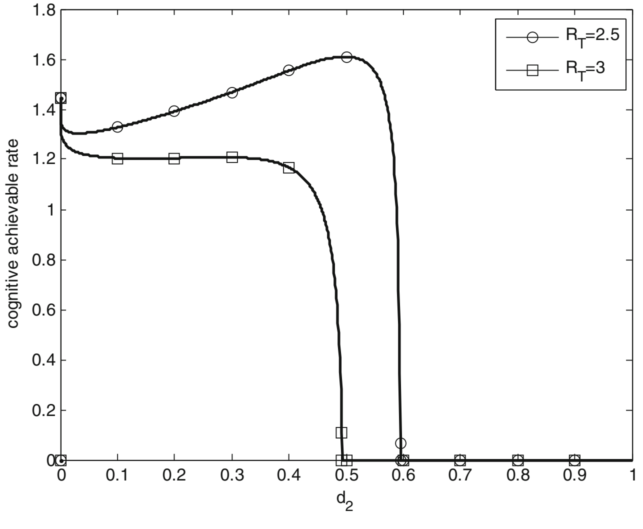

Fig. 4. Value of R_c versus d_2 with different R_T

5 Conclusion

A spectrum sharing protocol of cognitive radio based on DF relaying is proposed in this paper. Specifically, *CT* decodes information and harvests energy with the received signal. Then, the accessed bandwidth of *CT* is divided into two parts. One part is used to forward $PT's$ signal to *PR* with the energy *Q*, and the other part is used to transmit

$CT's$ signal to CR by using its own energy. There will be no interference between primary and cognitive systems. Joint power splitting ratio and bandwidth allocation is studied to maximize the value of R_C while satisfying the constraint of primary transmission rate. Simulation results show that the proposed joint optimization strategy is beneficial to both the cognitive and primary system.

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