Spectrum Access Based on Energy Harvesting with Optimal Power Allocation

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Abstract. In this paper, we propose a spectrum access method based on energy harvesting with optimal power allocation. Specifically, in the first phase, the primary user broadcasts its signal. The cognitive user receives the primary signal, and splits the power into two parts, one is to decode information, another is to harvest energy. In the second phase, the cognitive user forwards the primary signal by using the power harvested in the first phase, whlich assists the primary user to achieve the target rate. The cognitive user can access the primary spectrum to transmit its own signal by using its own power as a reward. We study the optimal power allocation to maximize the cognitive achievable rate, meanwhile the target rate of the primary user is achieved. Simulation results indicate that the proposed method can improve the performances of both the primary and cognitive users.

Keywords: Energy harvesting · Power allocation · Spectrum access

1 Introduction

With the dramatic demand increase of wireless communications, the requirement of the data transmission rate of wireless communication is becoming so large that more spectrum resource is needed. However, the spectrum resource is limited, and there are different degrees of wastes in time and space of the spectrum resource allocated by the existing wireless systems, which restricts the development of wireless communications. Cognitive radio technology can utilize the idle spectrum resources, which is capable of effectively improving the spectrum utilization under the premise of not affecting the primary user's performance [1]. The power allocation optimization to obtain the maximal cognitive rate is researched in [2, 3], which the primary rate can be guaranteed with the constraint of the primary power.

Recently, cooperative diversity technology has been broadly applied in cognitive radio for spectrum access, since it enlarges the system coverage and increases the link reliability [4, 5] proposed a centralized cooperative spectrum leasing protocol, in which the primary user leased a part of its transmission time to the cognitive user transmitting its signal, and the cognitive user allocated a portion of the acquired transmission time to help transmit the primary signal. Distributed spectrum sharing protocols with

Q. Chen et al. (Eds.): ChinaCom 2016, Part II, LNICST 210, pp. 551–559, 2018.
DOI: 10.1007/978-3-319-66628-0_52

cooperative relay were proposed in [6, 7], where the cognitive user used parts of power to help transmit the primary signal to guarantee the primary target rate no worse than direct transmission, and the remaining power is used to transmit its own signal. We proposed spectrum access protocols based on OFDM relaying in [8, 9], the cognitive user plays a relay role to assist the primary user to achieve the target rate by using a portion of subcarriers to forward the primary signal, while the remaining are used to transmit its own signal.

However in these spectrum access methods, for the purpose of gaining the spectrum access, the cognitive user is required to contribute a part of its power to help forward the primary signal. The more power of the cognitive is split to forward the primary signal, the less power will be left for the cognitive user to transmit signal itself that may results in poor performance of the cognitive user. Then, the cognitive user will be unwilling to gain the spectrum access.

Wireless energy harvesting technology has drawn significant attention in wireless signal and power transmission. Different forms of energy harvesting are studied in [10–12]. In [10], a dynamic power splitting method based on energy harvesting was proposed, where the receiver allocates a part of the transmission power to decode information, and the remaining to harvest energy. In [11] a time switching method was presented, in which the receiver needs to select the different phases to decode information or harvest energy to maximize the system performance.

In this paper, we propose a spectrum access method based on energy harvesting with optimal power allocation, where the cognitive user allocates a part of the power obtained from the received primary signal to harvest energy in the first phase, and uses the remaining power for information decoding. Then, in the second phase, the cognitive user utilizes the power harvested in the first phase to assist transmitting the primary signal to ensure the target rate. As a reward, the cognitive user can transmit its own signal by its own power by gaining the primary spectrum access. We study the optimal power allocation to obtain the maximal cognitive rate, given that the target rate of the primary user is achieved.

2 System Model

The system model is showed in Fig. 1. We can see that the primary system is composed of a primary transmitter (*PT*) and a primary receiver (*PR*) which supplies relay function and operates with a licensed spectrum W. The cognitive system consists of a cognitive transmitter (*CT*) and cognitive receiver (*CR*), which is seeking opportunity to gain the primary spectrum access to send its own signal.

We use the Rayleigh flat fading to model the channel coefficients of links $PT \rightarrow PR$, $PT \rightarrow CT$, $CT \rightarrow PR$ and $CT \rightarrow CR$, which are denoted as h_1, h_2, h_3 and h_4, respectively. We have $h_i \sim CN(0, d_i^{-v})$, $i = 1, 2, 3, 4$, where v denotes the path loss exponent, d_i denotes the normalized distance between *PT* and *PR*. $\gamma_i = \left|h_{i,k}\right|^2$ denotes the instantaneous channel gain of h_i. We further assume that all the channel coefficients are constant in the two phases.

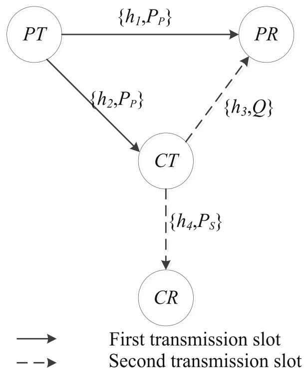

Fig. 1. System model.

3 Achievable Rates of Primary and Cognitive Users

Firstly, to consider the direct transmission, the primary user sends its signal to *PR* without cognitive user access. The primary user can achieve the rate that can be expressed as

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

where P_P is the transmit power of *PT* and σ^2 is additive Gaussian noise variance.

When R_D falls below the target rate R_T, as $PT \to PR$ is highly attenuated, e.g., due to strong shadow fading, *PR* will search for cooperation from the nearby cognitive users for the sake of improving the performance. Only the cognitive user who can assist guaranteeing the primary target rate will have the chance to access the spectrum of primary user. The cognitive user determines whether it can provide assistance for the primary user to reach the target rate within two phases.

In the first phase, *PT* broadcasts signal to *PR* and *CT*. *CT* allocates a part of the power obtained from the received primary signal to harvest energy, and utilizes the remaining to decode information. Thus, the achievable rates of $PT \to PR$ and $PT \to CT$ links can be written as

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

$$R_1 = \frac{1}{2}W\log_2(1 + \frac{\alpha\gamma_2 P_P}{\sigma^2}) \tag{3}$$

And the energy harvested at *CT* can be written as

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

where ε is a constant which represents the loss coefficient of transforming the energy to electric energy. It is assumed that $\varepsilon = 1$ in this paper for convenience.

In the second phase, CT uses the power Q, which is harvested in the first phase, to assist forwarding the primary signal. Consequently, $CT \rightarrow PR$ link can achieve the rate that can be shown as

$$R_2 = \frac{1}{2} W \log_2\left(1 + \frac{(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2 + \gamma_3 P_S}\right) \tag{5}$$

where P_S is the total transmit power of CT.

After two phases, the achievable rate of the primary user is

$$R_P = \min\{R_1, R_2\} \tag{6}$$

Meanwhile, CT uses its own power P_S to transmit its own signal to CR. Therefore, the rate the cognitive user achieves is expressed as

$$R_S = \frac{1}{2} W \log_2\left(1 + \frac{\gamma_4 P_S}{(1-\alpha)\gamma_2\gamma_4 P_P + \sigma^2}\right) \tag{7}$$

4 Optimal Power Allocation

We study the optimization of power α for the purposes of not only maximizing the cognitive user's rate R_S, but also ensuring the primary target rate R_T. Consequently, the optimization problem is written as

$$\max_{\alpha} R_S \tag{8}$$

Subject to

$$\begin{cases} R_P \geq R_T \\ 0 < \alpha < 1 \end{cases} \tag{9}$$

Substituting (3), (5), (6), (7) and (8) into (9), we can obtain

$$\max_{\alpha} \frac{1}{2} W \log_2\left(1 + \frac{\gamma_4 P_S}{(1-\alpha)\gamma_2\gamma_4 P_P + \sigma^2}\right) \tag{10}$$

Subject to

$$\begin{cases} \frac{1}{2} W \log_2\left(1 + \frac{\alpha\gamma_2 P_P}{\sigma^2}\right) \geq R_T \\ \frac{1}{2} W \log_2\left(1 + \frac{(1-\alpha)\gamma_2\gamma_3 P_P}{\sigma^2 + \gamma_3 P_S}\right) \geq R_T \\ 0 < \alpha < 1 \end{cases} \tag{11}$$

We convert the first condition of (11) and obtain

$$\alpha \geq \frac{\sigma^2 M}{\gamma_2 P_P} \tag{12}$$

where $M = 2^{2R_T/W} - 1$. Then we convert the second condition of (11) and finally obtain

$$\alpha \leq 1 - \frac{M\left(\sigma^2 + \gamma_3 P_S\right)}{\gamma_2\gamma_3 P_P} \tag{13}$$

Thus, we can obtain

$$\frac{\sigma^2 M}{\gamma_2 P_P} \leq \alpha \leq 1 - \frac{M\left(\gamma_3 P_S + \sigma^2\right)}{\gamma_2\gamma_3 P_P} \tag{14}$$

From (7), we can find that R_S monotonically increases with α. Therefore, the optimal power allocation of the optimization problem can be written as

$$\alpha^* = 1 - \frac{M(\sigma^2 + \gamma_3 P_S)}{\gamma_2\gamma_3 P_P} \tag{15}$$

Substituting α^* into (7), we can obtain

$$R_S^* = \frac{1}{2}\log_2\left(1 + \frac{\gamma_3\gamma_4 P_S}{\gamma_4 M\left(\sigma^2 + \gamma_3 P_S\right) + \sigma^2\gamma_3}\right) \tag{16}$$

5 Simulation and Analysis of Power Allocation

We consider *PT*, *PR*, *CT* and *CR* are in a two-dimensional *X*-*Y* plane, where *PT* and *PR* are located are points $(0, 0)$ and $(1, 0)$, respectively, thus $d_1 = 1$. *CT* moves on the positive *X* axis, its coordinate is $(d_2, 0)$. *CR* is in the middle of *PR* and *CT*. Thus, $d_3 = 1 - d_2$, and $d_4 = 0.5d_3$. The path loss exponent denotes $v = 3$, $R_T = 1.5$ bps/Hz, $P_S/\sigma^2 = 10$, $W = 1$, unless otherwise specified.

The optimal power allocation with our proposed spectrum access method is showed in Fig. 2. With *CT* gradually becomes far away from *PT*, the power allocated to decode the primary signal will be smaller. This is because, when d_2 becomes larger, the $CT \rightarrow PR$ link obtains better SNR, from (5) we can find that the interference to primary user by reason of cognitive user will be larger. In the meantime the SNR of $PT \rightarrow CT$ link will be worse. Hence to guarantee the target rate of primary user, more power is needed of cognitive user to assist forwarding the primary signal, so that less power is obtained to decode the signal at CT.

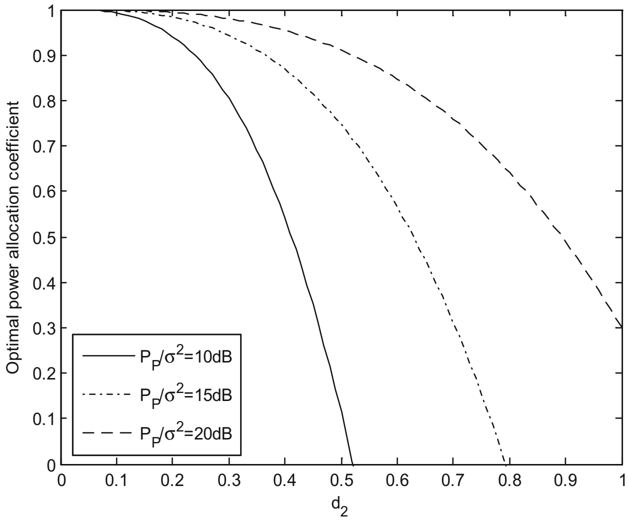

Fig. 2. Optimal power allocation versus different locations of *CT*

Figure 3 shows the cognitive achievable rate with our proposed spectrum access method. We can conclude that when the primary user gets larger power, the cognitive user will have larger region to gain the primary spectrum access. It is because the cognitive user can harvest more power from the primary user with larger power of the primary user. We can also observe from Fig. 3 that the cognitive user will achieve the same rate with different power of primary user within the access region for the reason that with the same target rate of the primary user, the cognitive user will harvest the same power to forward the primary signal. Thus, the interference to the cognitive user by reason of the primary user is the same. Then, with the same power of the cognitive user, the achievable rate will be same.

Figure 4 shows the optimal power allocation versus different power of CT. We can find that with larger target rate of the primary user, more power is needed to harvest at CT to help forward the primary signal. What's more, with smaller target rate of the primary user, the cognitive user will gain larger region to gain the primary spectrum access. Because the cognitive user will give more contribution to assist the primary user to achieve smaller target rate.

In Fig. 5, we can observe that the cognitive user will achieve larger rate with smaller target rate of the primary user. This is because, with smaller primary target rate, CT will harvest smaller power to assist forwarding the primary signal. Then, the interference caused to forward the primary signal to the cognitive user will be smaller. Thus, the cognitive user will achieve larger rate.

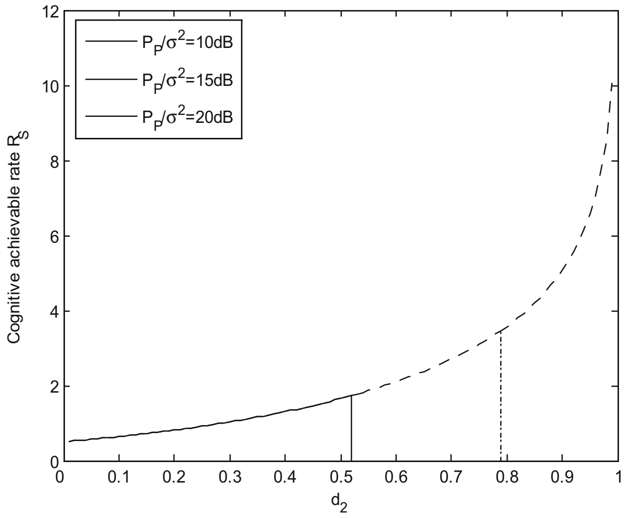

Fig. 3. Cognitive achievable rate versus different locations of CT

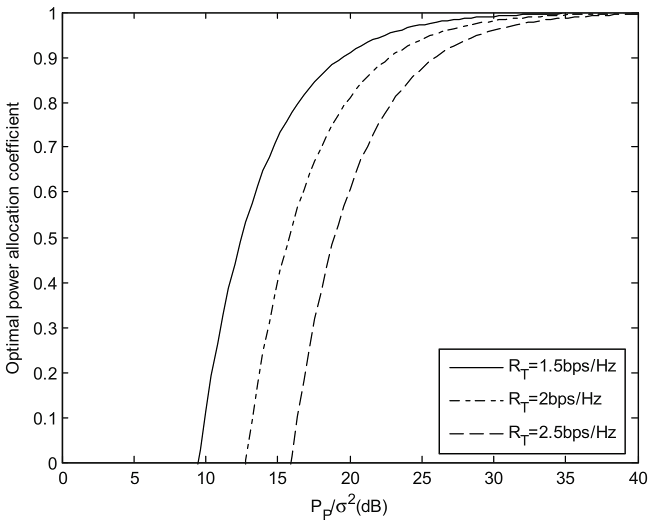

Fig. 4. Optimal power allocation versus different power of *PT*

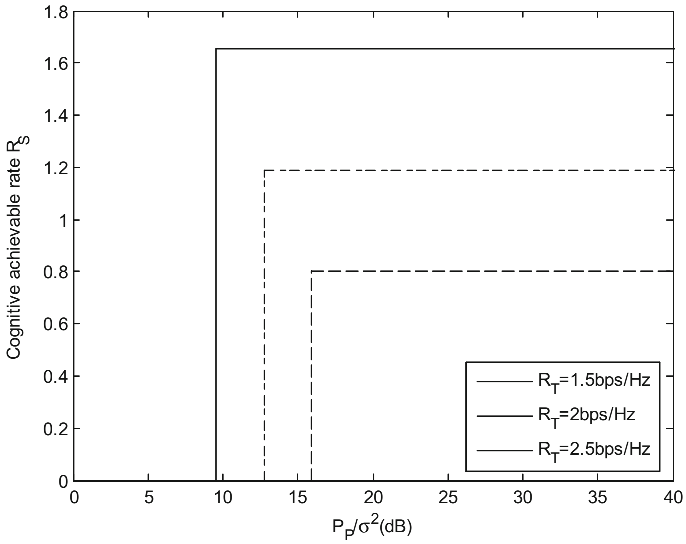

Fig. 5. Cognitive achievable rate versus different power of *PT*

6 Conclusion

We proposed a spectrum access method based on energy harvesting with optimal power allocation. The cognitive user plays a relay role to allocate a part of the power obtained from the received primary signal to harvest energy in the first phase, and uses the remaining power for information decoding. Then, in the second phase, the cognitive user can use the power harvested in the first phase to provide assistance to achieve the primary target rate by forwarding the primary signal. In return, the cognitive user is capable of accessing to the primary spectrum transmit its own signal by using its own power. We study the optimal power allocation to maximize the cognitive achievable rate, meanwhile the target rate of the primary user is achieved. Simulation results confirm that both the primary and cognitive users can improve the performance in our proposed method.

Acknowledgments. This work was supported by China National Science Foundation under Grant Nos. 61402416 and 61303235, Natural Science Foundation of Zhejiang Province under Grant Nos. LQ14F010003 and LQ14F020005, NSFC-Zhejiang Joint Fund for the Integration of Industrialization of Jiangsu Province under Grant No. BK20140828, the Fundamental Research Funds for the Central Universities under Grant No. DUT16RC(3)045 and the Scientific Foundation for the Returned Overseas Chinese Scholars of State Education Ministry.

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