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Simultaneous cooperative spectrum sensing and wireless power transfer in multi-antenna cognitive radio

Zhiqun Song [a,b], Zhongzhao Zhang [a], Xin Liu [c,*], Yutao Liu [b], Lisheng Fan [d]

[a] School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150080, China
[b] The 54th Research Institute of CECT, Shijiazhuang 050081, China
[c] School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
[d] School of Computer Science and Educational Software, Guangzhou University, Guangzhou 510006, China

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ABSTRACT

In multi-antenna cognitive radio (CR), the sensing performance of detecting the presence of primary user (PU) in fading channel can be improved through multi-antenna cooperative spectrum sensing. However, the CR may consume more stored energy due to the cooperative spectrum sensing and thus decrease its transmission performance. In this paper, to guarantee the transmission performance, a simultaneous cooperative spectrum sensing and wireless power transfer (SCSSWPT) scheme has been proposed, which can harvest the radio frequency (RF) energy of the PU signal to supply the consumed energy of spectrum sensing. Time splitting model, power splitting and antenna splitting model are proposed to implement cooperative spectrum sensing, energy harvesting and data transmission simultaneously. Three optimization problems have been formulated to maximize spectrum efficiency of the CR in the three SCSSWPT models, respectively, subject to the constraints of detection probability and harvested energy. The simulation results have shown that there is an optimal number of sensing antennas to maximize the spectrum efficiency of the CR, and the time splitting model can achieve higher spectrum efficiency.

1. Introduction

Wireless services have been explosively increasing in recent years [1–3], and many wireless transmission techniques have been proposed to tackle the demand [4–7]. Among these techniques, cognitive radio (CR), based on soft define radio, has been proposed to improve the current spectrum utilization through the flexible spectrum access. The CR can occupy the idle channel licensed to a primary user (PU) through sensing the absence of the PU [8–10]. However, the CR has to vacate the channel if the presence of the PU is detected. The traditional listen-before-talk transmission scheme has been proposed for the CR, in which the CR first uses some time for spectrum sensing and then accesses the spectrum with the left time at the absence of the PU [11]. However, the additional sensing time has to be consumed to decrease the transmission time [12,13]. Recently, multi-antenna technology, such as multiple-Input multiple-Output (MIMO), has been proposed to improve the transmission performance of the communication systems. Multi-antenna technology can make full use of the space resources and improve the channel capacity multiply without increasing the spectrum resources and the transmitting power of the antenna [14–17]. Hence, the multi-antenna technology can be used for CR to simultaneously perform spectrum sensing and data transmissions with different antennas.

Energy detection has been considered as an effective spectrum sensing method when the PU signal is unknown [18]. And the sensing decision can be made by comparing the energy statistic of the sensing signal to a predefined threshold. However, the energy detection performance may decrease obviously, when the PU signal to noise ratio (PSNR) is very low, such as multipath fading and shadow fading [19]. Cooperative spectrum sensing has been proposed to improve the energy detection performance, which can make a final decision by combining the local energy detection results from multiple CRs locating at different sensing areas. The sensing diversity gain can be obtained to cope with the signal attenuation [20,21]. Multi-channel cooperative spectrum sensing has been proposed to improve the detection performance of one single wideband SU by combining the local sensing results from different subchannels [22–24]. Similarly, the multi-antenna cooperative spectrum sensing can make a final decision by fusing the local sensing results from multiple sensing antennas.

Spectrum sensing may consume some circuit energy because of AD sampling, which can decrease the stored energy for data transmission. The sensing energy consumption rises with the increase of sampling nodes [25–27]. Thus, green CR has been investigated to

* Corresponding author.
E-mail address: liuxinstar1984@dlut.edu.cn (X. Liu).

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improve the energy efficiency of spectrum sensing, i.e., the green CR can achieve higher detection performance with less sensing energy [24]. However, the stored energy will still be consumed for spectrum sensing. Wireless power transfer technology has been proposed, which can collect the radio frequency (RF) energy of the nearby signal resources and then convert the RF energy to the direct current (DC) power, through deploying an energy-harvesting circuit consisting of band-pass filter, rectifying circuit and low-pass filter. The DC power is stored in a rechargeable battery of the communication system instead of a fixed power supply [28–31]. Wireless power transfer has been used in CR to harvest the RF energy of the PU signal, and the harvested energy can compensate the energy loss of spectrum sensing. However, the CR cannot implement spectrum sensing and energy harvesting at the same time [32,33]. A simultaneous wireless information and power transfer (SWIPT) has been investigated to harvest energy and process information simultaneously. Time splitting model and power splitting model have been proposed to realize SWIPT [34–36]. In the time splitting model, energy harvesting and information processing are implemented in different time slots, while in the power splitting model, energy harvesting and information processing are performed with different power streams. Based on the SWIPT, we have investigated the simultaneous cooperative spectrum sensing and wireless power transfer (SCSSWPT). The contributions of the paper are listed as follows

- A novel SCSSWPT scheme for a multi-antenna CR has been proposed to perform spectrum sensing, energy harvesting and data transmission at the same time. Multi-antenna cooperative spectrum sensing has be mathematically analyzed, whose false alarm probability and detection probability have been deduced, respectively.
- Three kinds of models have been investigated to realize the SCSSWPT, including time splitting model, power splitting model and antenna splitting model. In the time splitting model and the power splitting model, energy harvesting and spectrum sensing are performed in the same antenna set, while in the antenna splitting model, energy harvesting and spectrum sensing are implemented in independent antenna sets.
- Three optimization problems have been formulated to maximize spectrum efficiency of the CR in the three SCSSWPT models, respectively, subject to the constraints of detection probability and harvested energy. The optimization algorithms have been proposed to solve the proposed optimization problems.

The rest of the paper is organized as follows. The system model is proposed in Section 2, where the multi-antenna cooperative spectrum sensing is analyzed and the wireless power transfer is described. Then the three SCSSWPT models, including time splitting model, power splitting model and antenna splitting model, are respectively described and optimized in Section 3. The system performance is simulated and discussed in Section 4. Finally, the conclusions are drawn in Section 5.

2. Preparatory knowledge

We consider a CR system deploying N antennas and a PU system communicating with one antenna. The CR system has the functions of multi-antenna cooperative spectrum sensing and energy harvesting.

2.1. Multi-antenna cooperative spectrum sensing

In this paper, multi-antenna cooperative spectrum sensing is used to detect the presence of the PU, in which each antenna senses the PU by energy detection and a final decision is made through combining the sensing results of all the sensing antennas. Multi-antenna cooperative spectrum sensing can improve the detection performance by achieving sensing diversity gain, i.e., if the sensing performance of one antenna is weak, the total sensing performance will not be decreased through combining the sensing results from other sensing antennas. The energy detection of each antenna can be seen as a binary hypothesis problem as follows

$$y(m) = \begin{cases} h(m)s(m) + n(m), H_1 \\ n(m), H_0 \end{cases}, m = 1, 2, \ldots, M \tag{1}$$

where $y(m)$ is the received signal sample, $s(m)$ is the PU signal sample, $n(m)$ is the Gaussian noise sample, $h(m)$ is the channel gain between the PU and the SU, and M is the number of the sampling nodes; H_0 and H_1 denote the absence and the presence of the PU, respectively. $P(H_0)$ and $P(H_1)$ are the probabilities of H_0 and H_1, which satisfy $P(H_0) + P(H_1) = 1$. Supposing the sensing time is T and the sampling frequency is f_s, we have $M = Tf_s$. The energy statistic of the received signal is given as follows

$$\Gamma(y) = \frac{\sum_{m=1}^{M} \|y(m)\|^2}{M}. \tag{2}$$

Since $y(1), y(2), \ldots, y(M)$ are independent and identically distributed, according to the Central Limit Theorem, When M is large enough, $\Gamma(y)$ obeys the Gaussian distributions as follows

$$\Gamma(y) \sim \begin{cases} \mathcal{N}\left((1+\gamma)\,\sigma_n^2, \dfrac{(1+\gamma)^2\sigma_n^4}{M}\right), H_1 \\ \mathcal{N}\left(\sigma_n^2, \dfrac{\sigma_n^4}{M}\right), H_0 \end{cases} \tag{3}$$

where σ_n^2 is the noise power and $\gamma = \frac{\|s(m)\|^2\|h(m)\|^2}{\|n(m)\|^2}$ is the PSNR. Energy detection obtains the decision by comparing the energy statistic to a predefined threshold λ. Detection probability and false alarm probability are respectively given as follows

$$P_d = P_r(\Gamma(y) > \lambda | H_1) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - \gamma - 1\right)\sqrt{\frac{Tf_s}{(1+\gamma)^2}}\right) \tag{4}$$

$$P_f = P_r(\Gamma(y) > \lambda | H_0) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{Tf_s}\right) \tag{5}$$

where the function $Q(x)$ is described as follows

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} \exp\left(-\frac{\omega^2}{2}\right) \mathbf{d}\omega. \tag{6}$$

In multi-antenna cooperative spectrum sensing, the total energy statistic is obtained by accumulating the energy statistic of each antenna, which is given as follows

$$\Gamma(Y) = \sum_{n=1}^{N} \Gamma(y_n) = \frac{\sum_{n=1}^{N}\sum_{m=1}^{M} \|y_n(m)\|^2}{MN} \tag{7}$$

where N is the number of sensing antennas. Then the detection probability and the false alarm probability of cooperative spectrum sensing are respectively given as follows

$$Q_d = Q\left(\left(\frac{\lambda}{\sigma_n^2} - \bar{\gamma} - 1\right)\sqrt{\frac{NTf_s}{(1+\bar{\gamma})^2}}\right) \tag{8}$$

$$Q_f = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{NTf_s}\right) \tag{9}$$

where $\bar{\gamma}$ is the average PSNR of N subchannels.