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Spectrum-energy-efficient sensing with novel frame structure in cognitive radio networks

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ABSTRACT

Cooperative spectrum sensing (CSS) is a promising technology in spectrum sensing with an admirable performance. In this paper, we define a utility function which jointly considers the spectrum-efficiency and the energy-efficiency. In a single-user sensing scenario, by maximizing the utility function, a rigorous analytical expression for the optimal threshold of the energy detector is derived. In CSS, the general frame structure is inefficient since the time consumed by reporting contributes little to the sensing performance. In this paper, we propose a novel CSS frame structure, in which one secondary user's (SU's) reporting time is also used for other SUs' sensing. For time varying channels, collecting the sensing results at different time points is expected to achieve a time diversity gain for a SU, then the novel multi-minislot CSS scheme is proposed. In CSS, the optimal randomized rule and the optimal final decision threshold are derived. Simulation results show a significant improvement of the utility by using the proposed multi-minislot CSS scheme. It is also shown that there exists an optimal number of cooperating SUs that maximizes the utility, and the optimal number decreases as the price of the sensing energy increases.

1. Introduction

To alleviate the spectrum scarcity problem in wireless communications, cognitive radio (CR) systems [1] have been proposed as a means of filling the spectrum vacancy in time or space [2]. Cognitive radio enables opportunistic access to unused licensed spectrum bands. The SUs first sense the activities of primary users (PUs) and then access the spectrum white spaces if no primary activities are detected [3]. While sensing accuracy is important for avoiding interference to PUs, reliable spectrum sensing is not always guaranteed, due to the multipath fading, shadowing and hidden terminal problem. Cooperative spectrum sensing has thus been proposed to improve the sensing performance [4,5].

There are two parameters associated with spectrum sensing: probability of false alarm and probability of detection [6,7]. From the SUs' perspective, the lower the probability of false alarm, the more chances the channel can be reused when it is available, thus the higher the spectrum-efficiency [8]. However, when the probability of detection decreases, the interference to PU increases. In [9], the dynamic sensing strategies were investigated to improve the efficiency of spectrum utilization. In [10], a cognitive relay transmission scheme was proposed to improve the spectrum efficiency. In [11], a source routing protocol based on on-demand routing and dynamic channel assignment was proposed to increase the packet delivery ratio. In high-mobility CR networks, a stability-capacity-adaptive routing scheme was proposed to achieve high packet delivery ratio [12]. In wireless mesh networks, novel channel assignment algorithms were proposed to improve the bandwidth utilization [13,14]. Considering the energy consumed by the SU to perform spectrum sensing, authors in [15] proposed energy and throughput efficient strategies for CSS in CR networks. However, the above papers do not jointly consider the spectrum-efficiency and the energy-efficiency. In this paper, we define a utility function from the economic viewpoint in noncooperative single-user sensing scenario, and the utility function jointly considers the spectrum-efficiency and the energy-efficiency. By maximizing the utility function, a rigorous analytical expression for the optimal threshold of the energy detector is derived. The threshold of the energy detector can be adjusted to enhance the spectrum-energy-efficiency of the CR system.

Although it is shown that the CSS can greatly enhance the sensing performance, additional complexity and overhead are needed in the data collection and the fusion process [16,17]. Most existing works (e.g. [18]) assume a general time frame structure in which spectrum sensing and results reporting are conducted separately in different time duration. It can be seen that the time

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consumed by reporting contributes little to the sensing performance and grows approximately linearly with the number of cooperating SUs. For instance, a PU activity change within the reporting step makes no difference to the final sensing decision.

In this paper, we propose a novel CSS frame structure in which SUs conduct spectrum sensing and results reporting concurrently. One SU's reporting time is also used for other SUs' sensing. In this way, each SU gets a longer sensing slot without additional time overhead. The framework of the novel CSS scheme provides a much longer sensing time than that of the general frame structure, which results in a better sensing performance and a larger utility. For time varying channels, combining multiple sensing results obtained by a SU at different time points is expected to achieve a time diversity gain. In this paper, the novel multi-minislot (MMS) CSS scheme is proposed, in which the sensing slot is split into multi-minislots. In this way, a time diversity gain in the sensing performance can be achieved in the local sensing step.

In CSS, from a spectrum-efficiency standpoint, one should use more SUs in cooperative sensing to achieve spectrum utilization as high as possible. From an energy-efficiency standpoint, one should use less SUs in cooperative sensing, since the energy consumed by spectrum sensing and results reporting grows approximately linearly with the number of cooperating SUs. To analyze the above issue, we define a utility function for CSS which jointly considers the spectrum-efficiency and the energy-efficiency. If the CR network detects the absence of PU successfully, it can realize the benefits of utilizing the spectrum. However, if the CR network mistakes the presence for the absence of PU, it should pay a penalty for missed detection because it causes interference to PU. Also, each SU should pay for consumption of sensing energy and transmission energy. Considering all the above aspects, there might exist an optimal number of cooperating SUs to maximize the utility function.

In this paper, we employ the randomized rule in the decision fusion center and analyze the corresponding performance for both perfect and imperfect reporting channels. In order to maximize the utility, the probability in the randomized rule should be adaptive to the threshold of the energy detector. Specifically, the optimal final decision threshold is derived for the randomized rule. Then, the optimal number of cooperating SUs in cooperative spectrum sensing is derived by maximizing the utility function. Simulation results show that the utility of the novel CSS scheme is much larger than that of the general CSS scheme, and combining the sensing results from the multiple minislots can achieve a time diversity gain in the sensing performance. Furthermore, we show the superiority of our proposed fusion rule with optimal final decision threshold over the conventional Majority rule in terms of the utility. We also show that there exists an optimal number of cooperating SUs that maximizes the utility, and the optimal number decreases as the price of the sensing energy increases.

The rest of this paper is organized as follows. Section 2 is devoted to optimization of utility function for single-user sensing. The novel multi-minislot cooperative spectrum sensing is introduced in Section 3. Section 4 is devoted to optimization of utility function for cooperative spectrum sensing. Simulation results are presented in Section 5, and concluding remarks are given in Section 6.

2. Optimization of utility function for single-user sensing

The frame structure of the opportunistic spectrum access cognitive radio systems studied so far consists of a sensing slot and a data transmission slot, as depicted in Fig. 1. The sensing duration is denoted as t_s, the total frame duration is denoted as T.

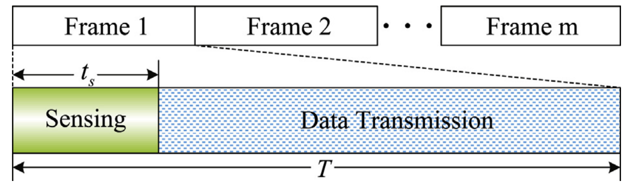

Fig. 1. Frame structure for cognitive radio networks with periodic spectrum sensing.

The essence of spectrum sensing is a binary hypothesis-testing problem [19]:

$\mathcal{H}_0$: the PU is absent;

$\mathcal{H}_1$: the PU is present.

The received signal $v_i(n)$ at the ith SU can be formulated as

$$v_i(n) = \begin{cases} \varepsilon_i(n), & \mathcal{H}_0 \\ h_i s(n) + \varepsilon_i(n), & \mathcal{H}_1 \end{cases} \tag{1}$$

where $n = 1, 2, \ldots, u$, u is the number of received signal samples collected at each SU during the sensing time. Hence, u is the product of the sensing duration t_s and the sampling frequency f_s. And $v_i(n)$ is the received signal at the ith SU, $s(n)$ is the signal from the PU, $\varepsilon_i(n)$ is the noise and is assumed to be independent and identically distributed (i.i.d.), real-valued Gaussian variable with zero mean and variance, $\mathbf{E}[|\varepsilon_i(n)|^2] = \sigma^2$. h_i is the channel gain between the PU and the ith SU. The SNR (signal-to-noise ratio) of PU's signal at the ith SU is then expressed as $\gamma_i = \frac{|h_i|^2 \mathbf{E}[|s(n)|^2]}{\sigma^2}$.

The decision statistic of energy detection is given by $V_i = \frac{1}{u}\sum_{n=1}^{u} |v_i(n)|^2 = \frac{1}{t_s f_s}\sum_{n=1}^{t_s f_s} |v_i(n)|^2$. Since the primary signals received at the SUs are considered to be i.i.d., we can omit the subscript 'i'. It is shown in [8] that when $t_s f_s$ is large enough, according to Central Limit Theorem, we have

$$V \sim \begin{cases} \mathcal{N}\left(\sigma^2, \dfrac{2\sigma^4}{t_s f_s}\right), & \mathcal{H}_0 \\ \mathcal{N}\left((\gamma+1)\sigma^2, \dfrac{2(2\gamma+1)\sigma^4}{t_s f_s}\right), & \mathcal{H}_1 \end{cases} \tag{2}$$

The probability density function (PDF) of V can then be written as

$$f_V(v) = \frac{\sqrt{t_s f_s}}{2\sigma^2\sqrt{\pi}} e^{-\frac{t_s f_s (v-\sigma^2)^2}{4\sigma^4}}, \quad \mathcal{H}_0 \tag{3}$$

$$f_V(v) = \frac{\sqrt{t_s f_s}}{2\sigma^2\sqrt{\pi(2\gamma+1)}} e^{-\frac{t_s f_s [v-(\gamma+1)\sigma^2]^2}{4(2\gamma+1)\sigma^4}}, \quad \mathcal{H}_1 \tag{4}$$

Then, the probability of false alarm and the probability of detection can be computed by [8]

$$p_f = P\{V > \lambda | \mathcal{H}_0\} = \int_{\lambda}^{\infty} f_{V|\mathcal{H}_0}(v) dv = \mathcal{Q}\left(\left(\frac{\lambda}{\sigma^2} - 1\right)\sqrt{\frac{t_s f_s}{2}}\right), \tag{5}$$

$$\begin{aligned} p_d &= P\{V > \lambda | \mathcal{H}_1\} = \int_{\lambda}^{\infty} f_{V|\mathcal{H}_1}(v) dv \\ &= \mathcal{Q}\left(\left(\frac{\lambda}{\sigma^2} - \gamma - 1\right)\sqrt{\frac{t_s f_s}{2(2\gamma+1)}}\right), \end{aligned} \tag{6}$$

where λ denotes the threshold of the energy detection, $\mathcal{Q}(\cdot)$ is the $\mathcal{Q}$-function defined as $\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}} dt$.

From the SUs' perspective, the lower the probability of false alarm, the more chances the channel can be reused when it is available, thus the higher the spectrum utilization. However, when the probability of detection decreases, the interference to PU increases.