Computer Communications 41 (2014) 67–75

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Optimal non-identical sensing setting for multi channels in cognitive radio networks

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ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 1 September 2013
Accepted 1 January 2014
Available online 10 January 2014

Keywords:
Spectrum sensing
Non-identical sensing
Cognitive radio

ABSTRACT

In this paper, optimal multiple channels cooperative spectrum sensing setting in non-identical environment is investigated. In previous works on cooperative sensing, the secondary users are assumed to have the same detection threshold and the noise received is assumed to be independent identically distributed random variable. Thus researchers often assume that identical sensing time is assigned to the channels for spectrum sensing. In our paper, secondary users cooperatively sense the channel and send the binary results to the common receiver where energy detection with hard decision rule is employed. We assume that secondary users can assign non-identical sensing time to the channel with possibly different noise powers and detection thresholds. An iterative algorithm with polynomial complexity is established to determine the optimal sensing sequence (which represents the order at which the secondary users sense the channels) for the secondary users to assign the mini-slots (minimum sensing unit) to sense the channels, such that the throughput increase can be maximized in each iteration. Furthermore, *delay sensitivity* is introduced as a new performance metric to evaluate how long the authorized transmitting users need to wait for data transmission. Simulation results show that our algorithm is highly effective in improving the achievable throughput and delay sensitivity.

1. Introduction

The rapid growth in wireless communications technologies has contributed to a huge demand on frequency spectrum. However, most of the spectrum is fixedly allocated to a set of special licensed users. Several studies have shown that large amount of allocated spectrum experiences a severe under-utilization problem [1,2]. This motivates us to consider cognitive radio technology which is proposed to allow the secondary users to utilize the licensed spectrum when it is not occupied by the primary users [3,4]. Secondary users are required to sense the spectrum before opportunistically accessing it. If the spectrum is occupied by a primary user, the secondary user has to defer its transmission in order to avoid causing harmful interference to the primary user. Hence, spectrum sensing is required to be performed before the secondary user can access the primary channel. The detection quality of spectrum sensing easily suffers from fading and shadowed environments, which can cause the hidden terminal problem. Cooperative spectrum sensing is therefore proposed to enhance the sensing performance. Multiple secondary users sense the spectrum independently, and send the binary decision results to the common receiver where the final decision is made to infer whether the spectrum is occupied by the primary user [5–9].

Currently, the spectrum sensing techniques can be mainly classified into matched filter, cyclostationary detection and energy detection [10,11]. Matched filter detection requires perfect knowledge of the PU's signaling features such as operating frequency, modulation type and order. Cyclostationary detection requires intensive signal processing which may not be feasible to implement. For real-time implementation without the need for secondary users to have a priori knowledge, energy detection [12–14] schemes are more suitable. One challenge is that the energy detection thresholds are dependent on the noise. There is actually a rich body of literatures on studying spectrum sensing [15–20]. However, most of them always assume that all the secondary users have the same energy detection threshold, and the primary signals received are independent identically distributed (i.i.d) random variables [15,16,18,19]. Moreover, both the average SNR and the noise power are identical at the different secondary users [17,20]. These assumptions are not always reasonable, due to the following facts [21]: (1) Secondary users are in different proximities from the primary user; (2) The noise power is not identical in reality. The irrationality of these assumptions will become more severe when the secondary network suffers from fading environment or mobility. Thus it may not be optimal to have all the secondary users with identical sensing time. In this paper we want to exploit the optimal sensing setting under the assumption that the secondary users have possibly different detection thresholds and noise powers. The work in [22] has shown that by allowing some secondary users not to

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http://dx.doi.org/10.1016/j.comcom.2014.01.001

participate in sensing so as to reserve more time for data transmission, the system performance can be improved. In this paper, we will investigate how each secondary user can assign different sensing time to the channel for spectrum sensing with possibly different energy detection thresholds and noise powers.

Two common decision-combining approaches have been proposed, hard decision (e.g. Each secondary user performs independent local spectrum sensing and reports the binary decision to the common receiver.) and soft decision (e.g. Each secondary user is required to send the full observation result to the common receiver.) [15,23,24]. Apparently, hard decision needs less data transmission. Moreover, if cooperative spectrum sensing is performed in multichannel environment, the sensing performance is further affected by these two decision-combining approaches in a different way. In [25], soft decision is employed to estimate whether the primary user is active, with this decision rule, only the total time used to sense the channel affects the performance of cooperative spectrum sensing, regardless of how this total time is distributed among the secondary users. However, in our paper, hard decision is chosen to combine the binary decisions from the secondary users; thus not only does the sensing sequence of the channels affect the cooperative spectrum sensing performance, but also the total time distributed among the secondary users. We attempt to determine the optimal sensing sequence (which secondary user should assign mini-slot to sense which channel) that maximizes the throughput increase in each step while improving the delay sensitivity at the same time.

This paper completes the analysis of non-identical sensing setting where the initial part of the work has been published in [28]. The major contributions of this paper can be listed as follows:

1. Detailed study of the optimal non-identical sensing setting under the assumption that the secondary users have different detection thresholds and noise powers. Non-identical sensing setting is a potentially effective way in reducing the sensing overhead.
2. An iterative algorithm with polynomial complexity is developed and implemented to determine the optimal sensing sequence that represents which secondary user should assign mini-slots to sense which channel. At each step, the sensing sequence selected is optimal, such that the throughput increase can be maximized.
3. Through extensive numerical experiments, it is verified that the proposed iterative algorithm outperforms the scheme which only allows the secondary users to assign identical sensing time to the channels for spectrum sensing.
4. A new performance metric *delay sensitivity* is defined to evaluate the sensing performance of the proposed iterative algorithm. It is shown that the authorized transmitting users suffer a lower delay for data transmission and meanwhile can achieve a higher throughput due to more time allocated for data transmission.

The rest of this paper is organized as follows. The overviews of the system model and spectrum sensing are introduced in Section 2. The throughput of secondary users is derived in Section 3. An iterative algorithm which is proposed to determine the optimal sensing sequence such that the throughput increase can be maximized is given in Section 4. Simulation performance evaluation and comparisons are detailed in Section 5. Finally, Section 6 concludes the paper.

2. Network model and spectrum sensing

In this section, the general network model for the non-identical sensing setting problem is presented followed by an overview of spectrum sensing.

2.1. Network model

We consider a system with M secondary users and N channels. Let $\mathbb{N} = \{1, 2, \ldots, N\}$ and $\mathbb{M} = \{1, 2, \ldots, M\}$ be the sets of channels and secondary users, respectively. Without loss of generality, we only consider $M \geqslant N$, which is always true in reality. Each channel is assigned to a primary user. However the primary user may not be active all the time. The secondary user can opportunistically utilize the channel when it is available, e.g. if the channel is not occupied by the primary user, the secondary users can detect this opportunity successfully and transmit their data. For each frame duration, we group N secondary users as authorized transmitting users and the remaining $M - N$ as non-transmitting users. There exist several policies to group the secondary users as authorized users (e.g., according to their *SNR* or the traffic arrival rate). In our paper, we propose the following policy to determine the authorized transmitting users for each data frame.

1. Initial selection of the authorized transmitting users $\mathcal{A}^{(1)} = \{i^{(1)}, j^{(1)}, k^{(1)} \ldots\}$. They are randomly selected by the common cognitive receiver at the beginning of the first frame, where $1 \leqslant i^{(1)}, j^{(1)}, k^{(1)} \ldots \leqslant M$ and $|\mathcal{A}^{(1)}| = N$, $\mathcal{A}^{(1)} \subset \mathbb{M}$.
2. Incrementing parameter h, which is randomly generated by the common receiver to derive the authorized transmitting users for the next frame. h is less than the number of cognitive users, $1 \leqslant h < M$.
3. The next authorized transmitting users are determined by

$$\mathcal{A}^{(d+1)} = (\mathcal{A}^{(d)} + h)\ mod\ M, d \geqslant 1 \tag{1}$$

where d indicates the dth frame, and both the plus and mod operations are applied to all the elements in $\mathcal{A}^{(d)}$. For example, the number of cognitive users (numbered 1–5) and channels are $M = 5$ and $N = 3$, respectively, the initially authorized transmitting users are $\mathcal{A}^{(1)} = \{1, 2, 3\}$, and if the increment parameter $h = 2$, then the next authorized transmitting users are $\mathcal{A}^{(2)} = \{3, 4, 5\}$, because

$$(\{1, 2, 3\} + 2)\ mod\ M = \{3, 4, 0\} \tag{2}$$

where residue 0 means secondary user 5 is selected. This grouping policy can guarantee each secondary user has almost equal chance to become authorized transmitting user. It can be observed that different values of the increment parameter $1 \leqslant h < M$ will have no affect on the sensing performance.

Each basic frame structure of the secondary user consists of a sensing phase and a data transmission phase, as shown in Fig. 1. The sensing time is divided into a number of mini-slots, each is used to sense one channel with duration δ. During the sensing phase, the secondary users can assign a number of mini-slots to a set of channels for spectrum sensing. Let $K = [k_1, k_2, \ldots, k_M]$, where k_i denotes secondary user i assigning k_i mini-slots for spectrum sensing. $L = [l_{i,j}]_{M \times N}$ where $l_{i,j}$ represents secondary user i assigning $l_{i,j}$ mini-slots to sampling channel j. Note that $k_i = \sum_{j=1}^{N} l_{i,j}$. Unlike [25], this paper allows secondary users to assign different sensing time to sense the channel. Fig. 1 depicts an example of sensing mode for $N = 3$ channels and $M = 3$ secondary users. It can be observed that secondary user 1 assigns 5 mini-slots for spectrum sensing, and the channel sensing sequence is $\{1, 3, 2, 2, 1\}$, which indicates $k_1 = 5, l_{1,1} = l_{1,2} = 2$ and $l_{1,3} = 1$. However, secondary user 2 only assigns 3 mini-slots for spectrum sensing and the sensing sequence is $\{1, 1, 3\}$, that is $k_2 = 3$ and $l_{21} = 2,\ l_{23} = 1$. The sensing sequence which represents how the secondary users assign the mini-slots to the channels is the optimization parameter. Note that the sensing sequence considered in our paper takes both the secondary users and channels into account, which is different from [32–34] that only consider channel sequence.