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RESEARCH ARTICLE

Cluster-based adaptive multispectrum sensing and access in cognitive radio networks

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ABSTRACT

Spectrum sensing and access have been widely investigated in cognitive radio network for the secondary users to efficiently utilize and share the spectrum licensed by the primary user. We propose a cluster-based adaptive multispectrum sensing and access strategy, in which the secondary users seeking to access the channel can select a set of channels to sense and access with adaptive sensing time. Specifically, the spectrum sensing and access problem is formulated into an optimization problem, which maximizes the utility of the secondary users and ensures sufficient protection of the primary users and the transmitting secondary users from unacceptable interference. Moreover, we explicitly calculate the expected number of channels that are detected to be idle, or being occupied by the primary users, or being occupied by the transmitting secondary users. Spectrum sharing with the primary and transmitting secondary users is accomplished by adapting the transmission power to keep the interference to an acceptable level. Simulation results demonstrate the effectiveness of our proposed sensing and access strategy as well as its advantage over conventional sensing and access methods in terms of improving the achieved throughput and keeping the sensing overhead low. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS

cognitive radio; spectrum sensing and access; utility; cooperative overhead

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1. INTRODUCTION

According to recent measurements by the Federal Communication Commission, most of the spectrum bands allocated to specific license users experience significant under-utilization [1,2]. To improve the spectrum efficiency as well as to support the growth of wireless technologies, cognitive radio [3,4] has evolved as a promising technology to attain much higher spectrum utility by opportunistic spectrum access (OSA) (which allows the secondary users to utilize the channel only when it is detected to be idle [5]) and spectrum sharing (SS) (which allows the secondary users to coexist with the primary user under condition of an acceptable interference [6]). Perhaps the most appealing property of cognitive radio is its ability to detect and characterize its wireless environment and adapt accordingly. With these capabilities, cognitive radio lends itself very well to detect the temporarily unused spectrum and operate in the licensed channels without causing any interference to the high priority users. Consequently, spectrum sensing performed by cognitive radio cannot be restricted to simply measuring the received energy in some channels of interest

but must include detection and signal classification in order to adapt their transmission power to avoid causing harmful interference [7].

1.1. Related work

To implement without interference to the primary user and the transmitting secondary user, spectrum sensing should be performed before accessing the channels. Currently, the spectrum sensing techniques can be mainly classified into matched filter, cyclostationary detection, and energy detection. Matched filter detection is considered as optimal for detection of primary users when the transmitted signal is known because it maximizes the received signal-to-noise ratio (SNR) [8]. However, one drawback of this method is that it requires perfect knowledge of the primary users signaling features such as operating frequency, modulation type, and order. Energy detection is the most common way of spectrum sensing because of its low computational and implementation complexity [9,10]. However, it is well known that energy detection is not robust to noise and incapable of differentiating signal types. On the other hand,

cyclostationary detection is robust to the noise and has the ability to discriminate the signal types, but it requires much higher sensing time and the prior knowledge of the detection signals [11,12]. Thus, to mitigate the demerits of these detection techniques while utilizing the individual merits, it is better to combine two or more methods. Two-stage detection method that performs energy detection in the first stage, followed by a cyclostationary detection, has been proposed in [13,14]. Following the previous studies, we consider a two-stage sensing method based on energy detection and cyclostationary detection. For a given channel, energy detection is performed in the first stage, if the detected energy is below a certain threshold, it is hypothesized that the channel under consideration is idle. Otherwise, if the energy is above the threshold, then a secondary stage analysis is carried out using cyclostationary detection to differentiate whether the channel is occupied by the primary user or the transmitting secondary user.

It is well known that the detection performance of local spectrum sensing is usually limited because of channel fading and shadowing. Recent work has shown that by taking advantage of spatial diversity with cooperative sensing, the reliability of spectrum sensing can be greatly improved [15,16]. In conventional cooperative spectrum sensing systems, each secondary user reports the observation to the common receiver through perfect channels, which is impractical because the channels between the cognitive users and the common receiver are usually subject to shadowing and fading [17]. A cluster-based cooperative spectrum sensing is proposed to improve the sensing performance [18], in which user selection diversity is exploited by selecting the most favorable user in each cluster to report the fusion results to the common receiver. To reduce the sensing delay and overhead, [19] only allows the secondary users who have enough information in each cluster to send the sensing results to the cluster head (CH). Cluster-based sensing strategies are further investigated in [20,21]. By far, most of the previous work discussing cluster-based sensing focus on the case that all the secondary users in the system select identical time for spectrum sensing. However, the work in [22] has shown that by allowing the secondary users to assign nonidentical sensing time, the excessive sensing overhead can be significantly reduced. In our work, we formulate the cluster-based sensing problem differently from [18–20] in several ways; most significant is that each cluster can adaptively select sensing time according to its own channel gain and traffic load. In addition, no common receiver is required; hence, information exchange between the CHs and the common receiver is not needed. Therefore, the sensing overhead will be reduced.

Recently, study on the optimization of spectrum sensing and access in cognitive radio network has attracted a lot of attention. In [23], an adaptive spectrum assessment (ASA) approach is proposed to decide how to seek spectrum opportunity effectively. A set of channels is sensed every time a discovery of new spectrum opportunity is triggered. The optimal number of sensed channels is derived

with the aim of keeping the overhead low as well as increasing the likelihood of discovering spectrum opportunity. Another commonly used approach is the sequential spectrum sensing (SSS) [24–27]. This SSS approach allows secondary user to explore diversity in the licensed spectrum by quickly continuing to identify another spectrum opportunity in case one channel is sensed busy. In [24], spectrum is searched by sensing the channels one by one until an idle channel is detected. However, previous studies on spectrum sensing and access in cognitive radio networks have focused primarily on the utilization of some portions of the licensed spectrum provided that the primary user is absent. A cognitive radio network is formed by either allowing the secondary users to opportunistically operate in the idle spectrum originally allocated to a primary user (refer to OSA) or by allowing the secondary users to coexist with the primary users as long as the interference caused by the secondary users to the primary users is properly regulated (refer to SS). SS has been studied by many works (e.g., [7,28,29]) and has been shown to improve the performance in terms of increasing the achieved throughput. From the primary user's perspective, secondary user is allowed to utilize the channel as long as the interference does not degrade the quality of service of the primary user to an unacceptable level. From the secondary user's perspective, the secondary user should adapt its transmit power to achieve a reasonably high transmission rate without causing too much interference to the primary user. In our work, we propose an adaptive multiple-channel sensing and access strategy that allows other secondary users to coexist with both the primary user and the currently transmitting secondary users while being subjected to some interference power constraints. The term "transmitting secondary users" will be used hereinafter to refer to secondary users who have already gained access to the channel and are transmitting. This is to differentiate them from other secondary users who are sensing the channels for transmission opportunities.

1.2. Motivation and contributions

In this paper, we investigate the design of the cluster-based adaptive sensing and access strategy for a cognitive radio network. The overall objective is to jointly design the sensing and access strategy to maximize the utility of the secondary users so as to balance the twin requirements of keeping the sensing overhead minimal and achieving maximum throughput. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the secondary users under the interference power constraints to the primary user and the transmitting secondary users. The main contributions of this paper are as follows.

Firstly, we propose a cluster-based sensing and access scheme, in which synchronization and cooperation only happen among the secondary users who belong to the same

cluster, and no common receiver is needed. By doing so, an adaptive sensing time scheme is used by each cluster, which allows different clusters to choose nonidentical sensing time based on their channel gains and traffic loads. With adaptive sensing time strategy and no information exchange between the CH and the common receiver, the sensing overhead will be significantly reduced.

Secondly, our proposed scheme allows the secondary users to sense and access multiple channels. Moreover, we explicitly calculate the expected number of channels that are idle or being occupied by the primary users or being occupied by the transmitting secondary users. SS with the primary user and transmitting secondary users is used by adapting the transmission power to avoid causing harmful interference. To the best of our knowledge, analysis has not been carried out with regards to studying the coexistence of both the primary user and the transmitting secondary user.

Finally, we derive a utility function that represents the tradeoff between the requirement to increase the achieved throughput and the desire to reduce the sensing overhead. In particular, we formulate the design of spectrum sensing and access into an optimization problem. The optimal number of channels that ought to be sensed is obtained numerically, such that the utility can be maximized. Simulation results illustrate that our proposed strategy outperforms ASA [23] and SSS [24].

1.3. Paper outline

The rest of this paper is organized as follows. Our system model is introduced in Section 2. The performance evaluation metrics of our proposed cluster-based spectrum sensing and access strategy are presented in Section 3. In Section 4, the problem analysis to calculate the expected number of channels that are idle, or being occupied by the primary users or being occupied by the transmitting secondary users, is developed. In addition, the spectrum sensing time that is adaptive to the channel gain and traffic load of the cluster is detailed. Simulation results and comparisons are presented in Section 5. Section 6 concludes the paper.

2. SYSTEM MODEL

In this section, we consider a simple cognitive radio network consisting of m primary users/channels and N secondary users. The primary users are the license holders and have the absolute priority to access the channels. However, the secondary users can opportunistically utilize the idle channels as well as share the occupied channels by adapting their transmitting power to avoid causing unacceptable level of interference to the primary users. In our model, we have defined earlier, *transmitting secondary user*, which is currently transmitting on the detected channels. The other secondary users who attempt to share the same channel as the transmitting secondary user should satisfy the interference power constraint.

Figure 1. The cluster-based system model for cognitive radio network.

The system architecture is illustrated in Figure 1. We assume that the secondary users are divided into K clusters by some distributed algorithms, which is out of the scope of this work, examples of which may be found in [30,31], where each cluster has N_i secondary users ($i = 1, 2, \dots, K$), and one of them is selected as the CH. From the beginning of each frame, cluster i will select l_i spectrum bands to sense. The set of channels to be sensed is selected by the CH and is distributed to the secondary users in the cluster.

Spectrum sensing is a key element in cognitive radio communications as it should first be performed before allowing OSA and sharing. We assume that each secondary user performs local spectrum sensing independently, and in the following, we take the analysis of cluster i as an example. Suppose the received signal is sampled with sampling frequency f_s , then the sampled received signal of the secondary user in cluster i for channel j ($1 \leq j \leq l_i$) has two hypotheses:

$$\begin{aligned} H_{1,(ij)} : & \quad y_{i,j}(n) = g_{ij}r_{i,j}(n) + u_{i,j}(n) \\ H_{0,(ij)} : & \quad y_{i,j}(n) = u_{i,j}(n) \end{aligned}$$

where $H_{0,(ij)}$ and $H_{1,(ij)}$ represent the channel is idle and busy, respectively. g_{ij} is the channel gain over the sensing channel j . n is the sample index ranging from $1 \leq n \leq \tau_i f_s$, τ_i is the sensing time of cluster i . $r_{i,j}(n)$ is the detected signal in channel j received by secondary users in cluster i with zero mean and variance $\sigma_{r_{i,j}}^2$. $u_{i,j}(n)$ is the independent white Gaussian noise experienced by the secondary user in cluster i from channel j with zero mean and variance $\sigma_{u_{i,j}}^2$. We further assume that the detected signal $r_{i,j}(n)$, regardless of primary signal or secondary signal, is independent of the noise $u_{i,j}(n)$.

We consider a two-stage sensing strategy based on energy detection and cyclostationary detection. At the first stage, energy detection is used; if the measured energy is

Figure 2. The model of two-stage sensing method with energy detection in the first stage, followed by cyclostationary detection.

below a certain threshold $\lambda_{i,1}$, then the channel is declared as idle. The idle channel can be utilized by secondary user without causing any harmful interference to the primary user and transmitting secondary user. On the other hand, the channels with detected energy that surpasses $\lambda_{i,1}$ are passed to the second stage where cyclostationary detection is used to distinguish between primary user and secondary user. If the signals belong to the primary users, then the secondary user can share the channels by keeping the interference to the primary users at an acceptable level. Otherwise, the channels are categorized as being occupied by the transmitting secondary users. Therefore, other secondary users who attempt to utilize these channels should adapt their transmitting power to satisfy the power constraints. The mechanism of two-stage spectrum sensing scheme that we propose is shown in Figure 2, and the detailed analyses of the energy detection and cyclostationary detection are discussed in the following.

2.1. Energy detection

The first stage of the proposed two-stage spectrum sensing approach is based on energy detection where the detector accumulates the energy of all the samples and then compares it with a certain threshold $\lambda_{i,1}$ to identify whether the channel is idle or not. The test decision statistic at the secondary user belonging to cluster i for channel j can be represented by

$$Y_{i,j} = \frac{1}{f_s \tau_i} \sum_{n=1}^{f_s \tau_i} |y_{i,j}(n)|^2 \quad (1)$$

The decision rule used by the energy detection is given by

$$Y_{i,j} \underset{H_{1,(ij)}}{\overset{H_{0,(ij)}}{\leq}} \lambda_{i,1} \quad (2)$$

If the noise $u_{i,j}(n)$ is circular symmetric complex Gaussian, then the false alarm probability $P_{f,(i,j)}^1$ that is defined as the probability of the secondary user falsely declaring the presence of the primary user or the

transmitting secondary user in channel j under $H_{0,(ij)}$ is given by [32]

$$P_{f,(i,j)}^1 = P[Y_{i,j} > \lambda_{i,1} | H_{0,(ij)}] = Q\left(\left(\frac{\lambda_{i,1}}{\sigma_{u_{i,j}}^2} - 1\right) \sqrt{f_s \tau_i}\right) \quad (3)$$

where τ_i is the sensing time for cluster i and the superscript “1” means the sensing stage. $Q(x)$ is the tail probability of the standard normal distribution, which is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$$

Furthermore, the detection probability $P_{d,(i,j)}^1$, which is defined as the probability that the secondary user correctly detects the busy status of channel j under $H_{1,(ij)}$, can be expressed as [32]

$$P_{d,(i,j)}^1 = P[Y_{i,j} > \lambda_{i,1} | H_{1,(ij)}] = Q\left(\left(\frac{\lambda_{i,1}}{\sigma_{u_{i,j}}^2} - 1 - \gamma_{i,j}\right) \sqrt{\frac{f_s \tau_i}{2\gamma_{i,j} + 1}}\right) \quad (4)$$

where $\gamma_{i,j}$ is the measured SNR of the detected signal in channel j received by secondary user in cluster i .

To protect the high priority users from interference by the secondary users, the detection probability in the first stage should not be less than a predefined threshold, that is, $P_{d,(i,j)}^1 \geq \alpha \geq 0.9$, for $\forall i, j$. Note that we set $\gamma_{i,j} = \min(\gamma_{i,j}^s, \gamma_{i,j}^p)$, where $\gamma_{i,j}^s$ and $\gamma_{i,j}^p$ denote the received SNR of the transmitting secondary user and primary user in channel j , respectively. Owing to the fact that the detection probability is a monotonically increasing function of SNR, to guarantee a target detection probability of the signal with smaller SNR, both the primary user and transmitting secondary user can be well protected. The false alarm probability can be rewritten as a function of α , that is,

$$P_{f,(i,j)}^1 = Q\left(\sqrt{2\gamma_{i,j} + 1} Q^{-1}(\alpha) + \gamma_{i,j} \sqrt{f_s \tau_i}\right) \quad (5)$$

2.2. Cyclostationary detection

The second stage of our proposed two-stage sensing method performs cyclostationary detection to differentiate

the signal types: for all the channels that previously are identified as busy, we estimate whether the channels are occupied by the primary or the secondary users. To lower power consumption and speed up spectrum sensing, one-order cyclostationary detection scheme that exploits the mean characteristics of the received signals is used [14]. Suppose the received signal can be modeled as

$$y_{i,j}^{(\epsilon)}(n) = r_{ij}^{(\epsilon)} e^{j(2\pi f_{ij}^{(\epsilon)} n + \theta_{ij}^{(\epsilon)})} \quad (6)$$

where $r_{ij}^{(\epsilon)}$, $f_{ij}^{(\epsilon)}$, and $\theta_{ij}^{(\epsilon)}$ are the amplitude, frequency, and phase of the received signal on channel j , respectively. The superscript $\epsilon = 1, 2$ represents the primary or the secondary signal, respectively. The mean function of $y_{i,j}^{(\epsilon)}(n)$ can be expressed as

$$M_{i,j}^{(\epsilon)}(n) = \frac{1}{2\tau_i f_s + 1} \sum_{n=0}^{2\tau_i f_s} y_{i,j}^{(\epsilon)}(n) \quad (7)$$

The operation of this one-order cyclostationary detection is to measure the envelope of the mean $M_{i,j}^{(\epsilon)}(n)$ and compare it with the predetermine threshold $\lambda_{i,2}$. Then, the false alarm probability, the detection probabilities for primary user and secondary user are given by

$$P_{f,(i,j)}^2 = 1 - \exp\left(-\frac{(2\tau_i f_s + 1)\lambda_{i,2}^2}{2\sigma_{u_{i,j}}^2}\right) \quad (8)$$

$$P_{d_p,(i,j)}^2 = Q\left(\frac{\sqrt{2\gamma_{ij}^p}}{\sigma_{u_{i,j}}}, \frac{\lambda_{i,2}\sqrt{2\tau_i f_s + 1}}{\sigma_{u_{i,j}}}\right) \quad (9)$$

$$P_{d_s,(i,j)}^2 = Q\left(\frac{\sqrt{2\gamma_{ij}^s}}{\sigma_{u_{i,j}}}, \frac{\lambda_{i,2}\sqrt{2\tau_i f_s + 1}}{\sigma_{u_{i,j}}}\right) \quad (10)$$

where $Q(\iota, \kappa)$ is the generalized Marcum Q-function, which is defined as

$$Q(\iota, \kappa) = \int_{\kappa}^{\infty} x e^{-(x^2 + \iota^2)} I_0(\iota x) dx$$

here, $I_0(x)$ is the first-order Bessel function.

In this two-stage sensing method, a false alarm happens under hypothesis $H_{0,(i,j)}$; if false alarm occurs at both two stages, hence, the overall false alarm probability is given by

$$P_{f,(i,j)} = P_{f,(i,j)}^1 P_{f,(i,j)}^2 \quad (11)$$

Similarly, the overall detection probabilities for secondary user and primary user are given by

$$P_{d_s,(i,j)} = P_{d_s,(i,j)}^1 P_{d_s,(i,j)}^2 \quad (12)$$

$$P_{d_p,(i,j)} = P_{d_p,(i,j)}^1 P_{d_p,(i,j)}^2 \quad (13)$$

Then, the classification of the primary user and the secondary user is carried out using amplitude $r_{ij}^{(\epsilon)}$, frequency $f_{ij}^{(\epsilon)}$, and phase parameters $\theta_{ij}^{(\epsilon)}$. Azzouz and Nandi [33] proposes an identification algorithm to classify the signal types (as depicted in Figure 1 of [33]). We do not fully introduce this method here as the detailed implementation is found in [33]. Moreover, if the secondary user has prior knowledge of signal modulation type, cyclostationary feature analysis, such as spectral correlation density and spectral coherence function, can be viewed as a useful tool for signal classification because of its important property that different modulated signals with the same power spectral density have highly distinct spectral correlation densities/spectral coherence functions [34]. That is, the signal r_j is declared to be present if a spectral component is detected at the corresponding cycle frequency. One example can be referred to [34].

2.3. Cluster-based cooperative spectrum sensing

Figure 1 describes the system structure of our cluster-based spectrum sensing and access method. At first, all the secondary users in cluster i carry out local two-stage spectrum sensing and make individual decision. Then, the CH collects and combines the sensing observations from the secondary users in the cluster, makes the decision on the availability of the spectrum, and then disseminates the results. We assume that cooperative spectrum sensing is adopted within the cluster. With the purpose of protecting the primary user and the transmitting secondary user, OR decision fusion rule is used. This rule demonstrates that the CH informs that the signal is being transmitted, when there exists at least one secondary user inferring that. Therefore, the cooperation detection probabilities for the primary and secondary signals is given by

$$Q_{d_p,(i,j)} = 1 - \prod_{h=1}^{N_i} (1 - P_{d_p,(i,j)}) \quad (14)$$

$$Q_{d_s,(i,j)} = 1 - \prod_{h=1}^{N_i} (1 - P_{d_s,(i,j)}) \quad (15)$$

Similarly, the cluster-based cooperative spectrum sensing false alarm probability is formulated as

$$Q_{f,(i,j)} = 1 - \prod_{h=1}^{N_i} (1 - P_{f,(i,j)}) \quad (16)$$

One should note that our proposed cluster-based sensing and sharing scheme differs from other existing conventional cluster-based sensing methods [18] in the following ways:

- (1) Cooperative spectrum sensing only happens within the same cluster. There is no common receiver; thus, CHs are not required to forward their decision to the common receiver. By doing so, all the secondary users experience a reduction in the latency and energy consumption.
- (2) Each cluster can select its sensing time adaptively according to the conditions, for example, traffic load and channel gain, which will be further discussed. Moreover, there is no synchronization among clusters. Each cluster can determine when to start and finish spectrum sensing.
- (3) Each cluster can select a set of channels to sense, and all these detected spectrum bands are shared by the secondary users in the same cluster. One example of sharing the detected channels may be found in [35]. We assume that all the secondary users in the same cluster are of the same quality in terms of detection characteristic and the transmission rate. Two-stage detection method is used to differentiate if the channel is occupied by the primary user or the transmitting secondary user.

2.4. Traffic load of primary and secondary users

There may be multiple clusters in the network all of which simultaneously seek spectrum opportunities in all the channels. We assume that the secondary traffic in cluster i is generated according to the poisson process with arrival related to the parameter ζ_i (there are N_i secondary users in cluster i , thus the total traffic arrival rate is $N_i\zeta_i$). The duration of service time is exponentially distributed with parameter μ_i . Therefore, let $\eta_i = \frac{N_i\zeta_i}{\mu_i}$ represent the traffic load of cluster i .

Experimental results indicate that modeling the traffic of wireless local area network users as a continuous-time semi-Markov process is shown to be a good approximation [36–38]. In particular, as explained in [37], the simplifying Markovian assumption, although not necessarily accurate across the entire traffic regime, seems to have a reasonably good fit with the measured data. Therefore, in our paper, the primary user's traffic on the channel is assumed to follow a continuous time Markov chain with two states: idle (OFF) and busy (ON) states. The time distributions of the idle and busy states of the primary user are assumed to be exponential distributions with parameters ζ_p and μ_p , respectively. That is

$$f_I(t) = \frac{1}{\mu_p} \exp\left(-\frac{t}{\mu_p}\right) \quad (17)$$

$$f_B(t) = \frac{1}{\zeta_p} \exp\left(-\frac{t}{\zeta_p}\right) \quad (18)$$

Let $\rho = \frac{\zeta_p}{\mu_p}$ denote the traffic load of the primary user. The average probability that a spectrum is being used by the primary user can be approximated as

$$P_b = \frac{\zeta_p}{\zeta_p + \mu_p} = \frac{\rho}{1 + \rho} \quad (19)$$

3. PERFORMANCE METRICS OF PROPOSED CLUSTER-BASED SPECTRUM SENSING AND ACCESS STRATEGY

In the following section, we derive some performance metrics that can evaluate our proposed cluster-based adaptive multiple-channel sensing and access strategy.

3.1. Cooperative sensing overhead

Each basic frame structure T of the secondary users consists of a sensing phase, a cooperation phase, and a data transmission phase. Let τ_i be the local sensing time, which is the time consumed by each secondary user to sense each channel for each stage. We assume that cluster i can select l_i spectrum bands to sense among the m bands. Thus, the sensing time is related to l_i . T_r^i denotes the cooperation time that contains the reporting time to the CH, the fusion time to make a final decision and the dissemination time to disseminate the result to the cluster members. Both τ_i and T_r^i will be further analyzed.

The cooperative sensing overhead of detecting available spectrum by sensing l_i channels can be expressed as

$$T_c^i = 2N_i l_i \tau_i + T_r^i \quad (20)$$

where T_r^i mainly depends on the number of cooperative users in cluster i . For simplicity, we assume $T_r^i = N_i T_p$, where T_p denotes the average time consumed by each secondary user from the time it starts to forward the sensing result to the CH until a final decision is obtained. Thus, T_c^i is given by

$$T_c^i = N_i (2\tau_i l_i + T_p) \quad (21)$$

Then, the actual amount of time within a frame to be used for data transmission is $T - 2l_i \tau_i - T_p$. As seen from (21), the differences in the time overhead among the clusters are independent of T_p , which is fixed for each secondary user. Therefore, the cooperative sensing overhead T_c^i is mainly determined by the local sensing time τ_i , the number of cooperative secondary users, and the number of channels that ought to be sensed.

3.2. Average achieved throughput

In the following, we describe how the proposed cluster-based sensing and sharing scheme operates and present the transmission rate of the secondary users based on the decision made by spectrum sensing. At the beginning of each frame, an initial spectrum sensing is carried out to detect the status of the frequency bands. On the basis of the decision of the spectrum sensing, the secondary users will communicate using higher power P_0 if both the primary user and the transmitting secondary users are detected to be absent ($H_{0,(ij)}$), whereas a lower power P_1 will be selected if the spectrum is sensed to be occupied by the transmitting secondary user ($\epsilon = 2$) and the lowest power P_2 is chosen if the primary user is detected ($\epsilon = 1$). Note that we have $P_0 > P_1 > P_2$ because the primary user has the highest priority and hence more protection should be accorded. Following the definition in [6,28,29,39], the instantaneous transmission rates of the secondary users on channel j , denoted by $r_{0,(ij)}$ for the case of $H_{0,(ij)}$, by $r_{s,(ij)}$ for the case of $\epsilon = 2$, and by $r_{p,(ij)}$ for the case of $\epsilon = 1$, are given by

$$r_{0,(ij)} = \log_2 \left(1 + \frac{|g_{ij}|^2 P_0}{\sigma_{u_{i,j}}^2} \right) \quad (22)$$

$$r_{s,(ij)} = \log_2 \left(1 + \frac{|g_{ij}|^2 P_1}{\sigma_{u_{i,j}}^2 + |g_{ij}|^2 P_0} \right) \quad (23)$$

$$r_{p,(ij)} = \log_2 \left(1 + \frac{|g_{ij}|^2 P_2}{\sigma_{u_{i,j}}^2 + |g_{ij}|^2 P_p} \right) \quad (24)$$

where P_p denotes the received power from the primary users. As discussed before, cluster i can select l_i spectrum bands to sense among the m bands. Let X_i , Y_i , and Z_i be the random variables that represent the number of channels that are detected to be idle, being occupied by the primary users and being occupied by the transmitting secondary users. The values depend on the activity of the primary users and the transmitting secondary users and the detected results. Their expected values are denoted by $E[X_i]$, $E[Y_i]$, and $E[Z_i]$, and their corresponding number of channels that can be shared are denoted by $E[X_i^*]$, $E[Y_i^*]$, and $E[Z_i^*]$, respectively, given that the average interference power constraints are upheld. An ergodic selection algorithm is developed in the next section to show how to obtain $E[X_i^*]$, $E[Y_i^*]$, and $E[Z_i^*]$ from $E[X_i]$, $E[Y_i]$, and $E[Z_i]$.

Then, the average achieved throughput of cluster i is given by

$$\Theta_i = \frac{T - 2l_i \tau_i - T_p}{T} \times (E[X_i^*] r_{0,(ij)} + E[Y_i^*] r_{p,(ij)} + E[Z_i^*] r_{s,(ij)}) \quad (25)$$

3.3. Sensing and access utility function

The main objective of this paper is to develop a multi-channel sensing and access scheme that allows the CH to determine the optimal number of channels that should be sensed with minimal sensing overhead as well as maximum achieved throughput. On one hand, by increasing the number of sensed channels, the more transmission opportunities can be discovered and more throughput can be achieved. On the other hand, the overhead incurred in the cooperative spectrum sensing increases when the number of selected sensed channels becomes larger and larger. Hence, it is an important issue to balance between the desire to improve the achieved throughput and the need to keep the sensing overhead low. We will introduce a utility function that represents the tradeoff between these two aspects and determine the optimal number of channels that ought to be sensed such that the utility can be maximized.

The utility function is defined as

$$U_i(N_i, \tau_i, l_i) = \Theta_i(N_i, \tau_i, l_i) - T_c^i(N_i, \tau_i, l_i) \quad (26)$$

Because the priority of a cognitive radio network is to protect the quality of service of the primary users, an interference power constraint should be imposed for protection. Therefore, we must limit the number of secondary users transmitting over the same busy channel to meet this constraint. Let S_j be the set of secondary users who are transmitting on channel j that is detected to be occupied by the primary user. Then, the average interference power to the primary user should be limited by $Q_{av,j}$, that is,

$$E \left[\sum_{h \in S_j} g_{hj} P_2 \right] \leq Q_{av,j} \quad (27)$$

Similarly, the average interference power to the transmitting secondary user must be considered as well. Let F_k be the set of secondary users who are transmitting on channel k that is declared to be occupied by the transmitting secondary user, and then, the average interference power impacting this transmitting secondary user will be bounded by $P_{av,k}$, that is,

$$E \left[\sum_{h \in F_k} g_{hk} P_1 \right] \leq P_{av,k} \quad (28)$$

where $Q_{av,j}$ and $P_{av,j}$ stand for the average interference power limits to the primary user and the transmitting secondary user on channel j , respectively.

Then, the multichannel sensing and access scheme can be formulated as an optimization problem, which maximizes the utility under some constraints on the interference to the primary user and the transmitting secondary user. The basic idea is as follows: At the beginning of each frame, the CH will select a set of channels for sensing.

On the basis of which, the expected number of channels that are idle, being occupied by the primary users and the transmitting secondary users are derived. The question arising here is which channels can be shared such that the constraints on the interference power to the primary user and the transmitting secondary users are upheld. The problem can be formulated as

Problem P1

$$\begin{aligned} \max_{l_i} \quad & U_i(N_i, \tau_i, l_i) \\ \text{s.t.} \quad & E \left[\sum_{h \in S_j} g_{hj} P_2 \right] \leq Q_{av,j} \\ & E \left[\sum_{h \in F_k} g_{hk} P_1 \right] \leq P_{av,k} \\ & 1 \leq j, k \leq l_i \end{aligned} \quad (29)$$

The objective and constraint functions in P1 are generally nonconvex, making it difficult to efficiently solve for the global optimum. In this work, we rely on numerical methods to solve the optimization problem P1 to find the optimal number of sensed channels such that the utility can be maximized.

3.4. Error rate

As will be discussed in the next section, we ignore the case when missed detection of the primary user and the transmitting secondary users occurs. However, the sensing performance is always measured by the error probability. Apparently, the higher the miss detection, the more serious impact the interference will cause. Imperfect detection may interfere with the transmission of the primary user and the transmitting secondary user. Therefore, the error due to missed detection should be taken into consideration. To do this, we define the error rate as

$$\xi_i = \frac{l_i - (E[X_i] + E[Y_i] + E[Z_i])}{l_i} \quad (30)$$

Note that because of missed detection, $E[X_i] + E[Y_i] + E[Z_i] \leq l_i$. Thus, the difference between the number of selected sensed channels l_i and the sum of the expected number of channels that are sensed to be idle, being occupied by the primary users and being occupied by the transmitting secondary users, provides an insight into the amount of errors that can be tolerated.

4. PROBLEM STATEMENT AND ANALYSIS

For each frame, depending on the activity of the primary user and the sensing results of the secondary users,

there exist six cases for cluster i , when performing spectrum sensing:

- Case 1:* The primary users are all active in the selected l_i spectrum bands, and the secondary users make a successful detection of the primary signals. Then, the secondary users will utilize these channels with transmit rate $r_{p,(ij)}$ under the interference power limit given by (27), for $j = 1, 2, \dots, l_i$.
- Case 2:* The primary users are all active in l_i spectrum bands, and all the secondary users fail to declare some of this busy condition. To protect the primary user, OR fusion rule is used, such that missed detection happens if and only if all the secondary users in cluster i mistake the busy channels as idle. We will neglect this case in analysis. Evaluation of missed detection will be conducted in the simulation.
- Case 3:* The l_i spectrum bands are all occupied by the transmitting secondary users and can be successfully detected by the secondary users in cluster i . Then, the secondary users will transmit with rate $r_{s,(ij)}$ over the l_i channels, under the interference power constraint given by (28), for $j = 1, 2, \dots, l_i$.
- Case 4:* The l_i spectrum bands are all occupied by the transmitting secondary users. However, missed detection happens. As per Case 2, we will not consider this case in the analysis.
- Case 5:* At least one or more spectrum bands are idle, and cluster i can correctly detect the transmission opportunity (not false alarm). Let $E[X_i]$ be the expected number of idle spectrum bands that are detected, and then, $E[X_i]$ spectrum bands can all be used by the secondary users with transmission rate $r_{0,(ij)}$.
- Case 6:* At least one or more spectrum bands are idle. However, false alarm occurs; thus, secondary users will transmit with lower power to avoid causing harmful interference to the primary user or the transmitting secondary users.

In the following, an adaptive sensing time scheme based on their own traffic loads and channel gains is proposed. The main goal of this section is to determine the likelihood that a given cluster finds some available channels. To make the mathematical analysis more tractable and easy to deal with, we break the problems into two steps. In the first step, we will calculate the probability that a particular spectrum band is detected to be idle, for example, neither occupied by the primary user nor the transmitting secondary user. In the second step, we obtain the expected number of idle channels. Furthermore, we will also obtain the expected number of spectrum bands that are occupied by the primary user and the transmitting secondary users. Finally, we will introduce an ergodic algorithm to select the channels that can be shared by the secondary users such that the interference power constraints are satisfied.

4.1. Adaptive sensing time scheme

In most existing work, researchers often assume that each secondary user has the same sensing time. However, the conditions of secondary users are different from one another, which implies that the sensing overhead may be reduced if the sensing duration of each secondary user adapts to its own condition. Consequently, an adaptive sensing time scheme is proposed for each cluster to detect the activity of the channels.

According to the aforementioned analysis, the search time of cluster i is given by

$$\tau_i = \vartheta(\eta_i, g_i)\tau \quad (31)$$

where τ is the identical local sensing time and $\vartheta(\eta_i, g_i)$ can be defined and set by the system designer. Intuitively, this factor depends on the characteristics of cluster i and should increase with η_i for a given g_i . It is reasonable because η_i can characterize the traffic load of cluster i . With a larger η_i , cluster i may keep transmitting for an amount of time, which implies that reliable and effective utilization of the channel is critical. We increase the sensing time to guarantee a lower collision probability as well as to decrease the false alarm probability that can alleviate the waste of transmission opportunity. On the contrary, if η_i is very small, which indicates that the traffic load of cluster i is low, we decrease the sensing time to avoid unnecessary spectrum sensing. On the other hand, the detection probability for a primary user to be present or absent in a licensed channel can be different among clusters because of their different geographical locations. For example, secondary users in a cluster that is further away from a primary user may have poorer detection quality than the cluster that is closer to the primary user. Thus, more sensing time is required to collect more samples by the secondary users in the cluster farther away from the primary user to improve the sensing performance. Therefore, as the distance increases, the factor $\vartheta(\eta_i, g_i)$ should increase as well to indicate that more sensing time is required because of the need to have more sampling observations, which enables the detection of very weak signals from the primary user. In this work, we choose

$$\vartheta(\eta_i, g_i) = \frac{\eta_i}{g_i} \quad (32)$$

where the channel gain g_i is decreased proportionally with the distance.

Therefore, the sensing time can be adaptive according to the characteristics of the secondary users to reduce the sensing overhead as well as to improve the sensing performance.

4.2. Idle probability of a particular spectrum

Here, we use Markovian analysis to model the spectrum condition with 2^{l_i} states given that no primary user

exists [23]. The model suggests that the secondary user activity forms an M/M/ $l_i/0$ queuing system. We denote the system state as $Q = (\phi_1, \phi_2, \dots, \phi_{l_i})$ that is an l_i -uplet of binaries, where $\phi_j, j = 1, 2, \dots, l_i$ denotes if spectrum j is occupied by a transmitting secondary user or not, that is,

$$\phi_j = \begin{cases} 1 & \text{if channel } j \text{ is idle} \\ 0 & \text{if channel } j \text{ is occupied} \end{cases} \quad (33)$$

Let Q_k denote the set of all the $\binom{l_i}{k} = \frac{l_i!}{(l_i-k)!k!}$ states that have exactly k spectrum bands occupied by the transmitting secondary users. Let π_k denote the steady state probability distribution representing that k channels are being occupied by the transmitting secondary users. Referring to the Erlang loss formula [40]

$$\pi_k = \frac{\frac{\eta^k}{k!}}{\sum_{l=0}^{l_i} \frac{\eta^l}{l!}}, \quad k = 0, 1, \dots, l_i \quad (34)$$

where $\eta = \sum_{i=1}^K \eta_i$ is the overall traffic load of all the clusters. Then, the probability that a particular spectrum band j_0 is busy because of being occupied by the transmitting secondary user is equal to the probability that the spectrum j_0 belongs to the set of spectrum bands that conducted Q_k , which is

$$\pi_{j_0} = \frac{\binom{l_i-1}{k-1}}{\binom{l_i}{k}} \pi_k = \frac{k}{l_i} \pi_k \quad (35)$$

Thus, the probability that a particular spectrum band j_0 is detected as idle, for example, neither occupied by the primary user nor the transmitting secondary user can be obtained as

$$\begin{aligned} p_{i,0} &= 1 - P_b - (1 - P_b) \sum_{k=0}^{l_i} \pi_{j_0} \\ &= 1 - \frac{\varsigma_p}{\varsigma_p + \mu_p} - \frac{\mu_p}{\varsigma_p + \mu_p} \sum_{k=0}^{l_i} \frac{k}{l_i} \frac{\frac{\eta^k}{k!}}{\sum_{l=0}^{l_i} \frac{\eta^l}{l!}} \end{aligned} \quad (36)$$

4.3. Expected number of idle spectrum bands

First, a spectrum band is considered actually idle if and only if (i) this spectrum band is not occupied by the primary user and (ii) the spectrum band is not occupied by the transmitting secondary user. Note that the second condition should be contained because all the secondary users compete for the spectrum. Secondly, an idle spectrum is assessed as idle through spectrum sensing if and only if a false alarm does not occur.

We introduce the following events:

- A_i : x_i spectrum bands are detected as idle for cluster i .
 B_i : a_i spectrum bands are actually idle among the selected l_i spectrum bands, $x_i \leq a_i \leq l_i$.

The probability that x_i spectrum bands are detected as idle can be obtained using the law of total probability, that is,

$$\begin{aligned} \Pr\{X_i = x_i\} &= \sum_{a_i=0}^{l_i} \Pr\{A_i|B_i\}\Pr\{B_i\} \\ &= \sum_{a_i=0}^{l_i} \left[\binom{a_i}{x_i} Q_{f,(i,j)}^{a_i-x_i} (1-Q_{f,(i,j)})^{x_i} \right. \\ &\quad \times \sum_{\Lambda \subset \Omega} \left[\prod_{\alpha \in \Omega-\Lambda} (1-p_{i,0}^{(\alpha)}) \prod_{\beta \in \Lambda} p_{i,0}^{(\beta)} \right] \Bigg] \end{aligned} \quad (37)$$

where Ω denotes the set of spectrum bands that are selected by cluster i to be sensed at each frame, and $|\Omega| = l_i$ and Λ are the set of spectrum bands that are actually not occupied by the primary users and the transmitting secondary users, $|\Lambda| = a_i$.

Therefore, the expected number of idle spectrum bands detected by cluster i is given by

$$E[X_i] = \sum_{x_i=0}^{l_i} x_i \Pr\{X_i = x_i\} \quad (38)$$

4.4. Expected number of spectrum bands occupied by primary users

We introduce the following events:

- C_i : y_i spectrum bands are detected as occupied by the primary users.
 D_i : b_i spectrum bands are actually busy because of the occupation of the primary users among the selected l_i spectrum bands of cluster i , $y_i \leq b_i \leq l_i$.

The probability that y_i spectrum bands are detected to be occupied by the primary users can be obtained using the law of total probability, that is,

$$\begin{aligned} \Pr\{Y_i = y_i\} &= \sum_{b_i=0}^{l_i} \Pr\{C_i|D_i\}\Pr\{D_i\} \\ &= \sum_{b_i=0}^{l_i} \left[\binom{b_i}{y_i} (1-Q_{d,p,(i,j)})^{b_i-y_i} Q_{d,p,(i,j)}^{y_i} \right. \\ &\quad \times \sum_{\Delta \subset \Omega} \left[\prod_{\alpha \in \Omega-\Delta} (1-p_b^{(\alpha)}) \prod_{\beta \in \Delta} p_b^{(\beta)} \right] \Bigg] \end{aligned} \quad (39)$$

where Δ is the set of spectrum bands that are actually occupied by the primary users, $|\Delta| = b_i$.

Therefore, the expected number of spectrum bands that are detected to be occupied by the primary users is given by

$$E[Y_i] = \sum_{y_i=0}^{l_i} y_i \Pr\{Y_i = y_i\} \quad (40)$$

4.5. Expected number of spectrum bands occupied by transmitting secondary users

The same discussion as the previously mentioned applies, that is, the probability that z_i spectrum bands are detected to be occupied by the transmitting secondary users can be obtained using the law of total probability, that is,

$$\begin{aligned} \Pr\{Z_i = z_i\} &= \sum_{c_i=0}^{l_i} \left[\binom{c_i}{z_i} (1-Q_{d,s,(i,j)})^{c_i-z_i} Q_{d,s,(i,j)}^{z_i} \right. \\ &\quad \times \sum_{\Psi \subset \Omega} \left[\prod_{\alpha \in \Omega-\Psi} (1-p_{i,s}^{(\alpha)}) \prod_{\beta \in \Psi} p_{i,s}^{(\beta)} \right] \Bigg] \end{aligned} \quad (41)$$

where Ψ is the set of spectrum bands that are actually occupied by the transmitting secondary users, $|\Psi| = c_i \leq l_i$ and $p_{i,s}$ is the busy probability of a particular spectrum band because of the occupation of the transmitting secondary users, that is,

$$p_{i,s} = \sum_{k=0}^{l_i} \frac{k}{l_i} \frac{\eta_i^k}{\sum_{l=0}^{l_i} \frac{\eta_i^l}{l!}} \quad (42)$$

The expected number of spectrum bands occupied by the secondary user is given by

$$E[Z_i] = \sum_{z_i=0}^{l_i} z_i \Pr\{Z_i = z_i\} \quad (43)$$

One should note that $E[X_i] + E[Y_i] + E[Z_i] \leq l_i$, because missed detection is not considered. The throughput achieved due to missed detection is not taken into account because the throughput will be very small even through it is achievable [22,32,41].

4.6. Ergodic selection algorithm

In the following, an ergodic selection algorithm is proposed to derive the expected number of channels that can be shared while the interference power constraints imposed for the primary user and the transmitting secondary users are upheld. The algorithm is conducted in three steps:

1. Firstly, all the detected idle channels can be utilized by the secondary users in cluster i , because no interference will incur, thus $E[X_i^*] = E[X_i]$.

- Secondly, set $E[Y_i^*] = 0$ and let R_i be a set that records the channels occupied by the primary users. Then, check the condition

$$E \left[\sum_{I \in S_j} g_{Ij} P_2 + g_{ij} P_2 \right] \leq Q_{av,j}, \quad \forall j \in R_i \quad (44)$$

if (44) holds, then we have

$$E[Y_i^*] = E[Y_i^*] + 1, \quad S_j = S_j \cup \{i\}$$

- Thirdly, set $E[Z_i^*] = 0$ and let H_i be a set that records the channels occupied by the transmitting secondary users. Then, check the condition

$$E \left[\sum_{I \in F_k} g_{Ik} P_1 + g_{ik} P_1 \right] \leq P_{av,k}, \quad \forall k \in H_i \quad (45)$$

if (45) holds, then we have

$$E[Z_i^*] = E[Z_i^*] + 1, \quad F_k = F_k \cup \{i\}$$

5. SIMULATION RESULTS

In this section, we present the simulation results and discussions for the proposed cluster-based multichannel sensing and access strategy and compare it with ASA in [23] and SSS in [24]. The parameters used in this system are as follows: the sampling frequency is fixed and set to $f_s = 6$ MHz, and the frame duration is $T = 200$ ms, the noise variance equals $\sigma_{u_{ij}}^2 = 1$ for all $j = 1, 2, \dots, m$. These are the same as in [42], whereas the average cooperation time is assumed to be $T_p = 1$ ms. We further set the identical local sensing time $\tau = 4.5$ ms and the transmission powers $[P_0, P_1, P_2, P_p] = [1, 0.5, 0.2, 4]$ dB.

5.1. Impact of secondary user traffic load

In Figure 3, we present the results for the utility of cluster i against the number of sensed channels for different secondary user traffic loads $\{0.3, 0.5, 0.7\}$. In this study, the primary user traffic load is set to $\rho = 0.5$. It can be observed that there exists an optimal number of channels that should be sensed such that the utility can be maximized. On one hand, the smaller the number of sensed channels, the less the channels that can be utilized and shared by secondary users, thus the lower the achieved throughput. On the other hand, increasing the number of sensed channels will improve the spectrum utilization but will incur a high overhead. Hence, we observe the trade-off phenomenon. Therefore, the optimal number of sensed channels balances the conflict between improving the achieved throughput and reducing the sensing overhead.

Moreover, it is easy to note that the utility decreases with an increase in the secondary user traffic load. This is reasonable because a larger η_i indicates a higher probability that the channel is occupied by the transmitting secondary user and less chance that the secondary users can transmit with a larger power.

Usually, we are more interested in the operating point where the optimal number of sensed channels achieves the maximum utility for each secondary user traffic load. However, as discussed before, it is difficult to efficiently obtain the closed expression of the optimal number of sensed channels by solving Problem P1. Here, we rely on numerical methods and plot the optimal number of sensed channels for different secondary user traffic loads in Figure 4. It is evident from the figure that the higher the secondary user traffic load, the larger the number of channels that should be sensed to maximize the utility.

Figure 3. The utility versus the number of sensed channels for different secondary user traffic loads and $\rho = 0.5$.

Figure 4. Optimal number of sensed channels versus secondary user traffic loads and $\rho = 0.5$.

Figure 5. The utility versus the number of selected sensed channels for different primary user traffic loads and $\eta_i = 0.5$.

5.2. Impact of primary user traffic load

Figure 5 depicts the utility as a function of the number of sensed channels for different primary user traffic loads $\{0.3, 0.5, 0.7\}$. In this study, the secondary user traffic load is set to $\eta_i = 0.5$. As illustrated in Figure 5, there exists an optimal value of the number of channels that ought to be sensed, such that the utility can be maximized. This can be explained using the same arguments as the preceding section. As expected, the lower the primary user traffic load, the higher the utility obtained. This is true because a smaller ρ means a higher probability that the channel is idle and hence more chance for the secondary user to transmit with a larger power.

5.3. Evaluation of error rate

In the following, to provide a better understanding on how our proposed cluster-based adaptive multichannel sensing and access scheme behaves, we evaluate the sensing performance by plotting the error rate as a function of the primary user traffic load for different secondary user traffic loads $\eta_i \in \{0.3, 0.5, 0.7\}$ and $l_i = 20$. As shown in Figure 6, it is clear that the error rate is far below 0.02, which indicates that the missed detection is small. Thus, our proposed strategy can provide sufficient protection to the primary users and the transmitting secondary users if the interference power constraints are satisfied.

5.4. Performance comparisons

To compare our proposed cluster-based adaptive multiple channels sensing and access strategy with other schemes, for example, ASA in [23] and SSS [24], we assume that there are $K = 5$ clusters in the system, with cluster sizes as $[10, 12, 8, 12, 8]$. For a fair comparison, we also assume

Figure 6. Error rate versus primary user traffic load for different secondary user traffic loads and $l_i = 20$.

that there are five communication groups seeking transmission opportunity in ASA and five independent secondary users performing SSS to explore idle channels. These two methods are briefly summarized as follows.

The ASA approach provides the secondary users with the capability of determining the optimal number of channels to be sensed when the discovery of new spectrum opportunities is triggered. If the communication group i successfully finds an opportunistic channel by sensing l_i channels, a reward (throughput) ω_i becomes associated with a cost (overhead). Therefore, we calculate the utility as follows:

$$U_{ASA} = \sum_{i=1}^K [q_i(m)\omega_i - (l_i \tau N_i + N_i T_p)] \quad (46)$$

where $q_i(m)$ is the probability that communication group i finds one available channel when sensing l_i channels in the system. Note that, because full collaborative sensing is used to protect the primary user, the certainty factor defined in [23] that represents how collaborative the sensing approach is will be set as 1. ω_i is equal to $r_{0,(ij)}$ because the secondary user can transmit when channel j is idle at a rate of $r_{0,(ij)}$ in our paper. Note that ASA in [23] is a distributed strategy, in which all the secondary users belonging to the same group exchange information for cooperation. Therefore, to implement full collaboration, each secondary user is required to exchange the sensing result with all the other secondary users. Whereas in our paper, each cluster member needs to exchange information with its CH, resulting in a low overhead. However, we assume the cooperative overhead per secondary user for ASA is T_p , which is smaller than actual. Thus, the cooperative overhead discussed here for ASA becomes a lower bound.

To reduce the sensing overhead, a widely used SSS [24] is proposed here for comparison, in which the secondary transmission is ceased as the channels have to be sensed

one-by-one until an idle channel is found. Let $\bar{T}_i$ denote the average time to sense the l_i channels, then $\bar{T}_i$ is given by

$$\begin{aligned}\bar{T}_i &= p_{i,0}\tau \sum_{k=1}^{l_i} k(1-p_{i,0})^{k-1} \\ &= \tau \left[\frac{1-(1-p_{i,0})^{l_i}}{p_{i,0}} - l_i(1-p_{i,0})^{l_i-1} \right] \quad (47)\end{aligned}$$

Then, the utility for SSS is

$$\begin{aligned}U_{SSS} &= \sum_{i=1}^K \left[\sum_{k=1}^{l_i} p_{i,0}(1-p_{i,0})^{k-1} r_{0,(ij)} \right. \\ &\quad \left. - (N_i \bar{T}_i + N_i T_p) \right] \\ &= \sum_{i=1}^K \left[\left[1 - (1-p_{i,0})^{l_i} \right] r_{0,(ij)} - (N_i \bar{T}_i + N_i T_p) \right] \quad (48)\end{aligned}$$

Figure 7 depicts the utility as a function of the number of channels in the system, obtained by our proposed strategy as well as the ASA in [23] and SSS in [24]. It can be observed that, in Figure 7, all of these methods have an optimal number of sensed channels such that the utility can be maximized. However, the optimal number of sensed channels derived for our method is much higher than ASA and SSS. This can be explained as follows: Our strategy allows the secondary users to access multiple idle channels and also coexist with the primary users and the transmitting secondary users under some interference power constraints. Thus, increasing the number of sensed channels will result in more transmission opportunities. As

Figure 7. The utility of the whole system versus the number of channels for our proposed strategy and existing adaptive spectrum assessment (ASA) [23] and sequential spectrum sensing (SSS) [24].

a result, the throughput can be improved despite increasing the sensing overhead. Whereas for ASA and SSS, as long as the idle channel is discovered, increasing the number of sensed channels will lead to a larger sensing overhead only. Consequently, as expected, our method has a larger value of optimal number of sensed channels.

It is evident from the figure that our proposed strategy can achieve a much higher utility than that achieved by ASA and SSS. That is, our method makes better use of the channel sensing and access by balancing the conflict between the achieved throughput and sensing overhead. By allowing multichannel access and sharing, the secondary users can utilize more channels by limiting the interference power to an acceptable level. Besides, the adaptive sensing time setting will further reduce the sensing overhead, thus the utility of our proposed strategy is higher than that of ASA and SSS. In addition, it is observed that SSS has better performance than ASA, because the spectrum sensing for SSS will be terminated as long as an idle channel is detected so as to avoid sensing the unnecessary channels. As for ASA, the selected channels will all be sensed, which increases the sensing overhead.

6. CONCLUSIONS

In this paper, we have studied the design of cluster-based multichannel sensing and access strategy in cognitive radio networks. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the secondary users under the interference power constraints imposed for the primary users and the transmitting secondary users. We assume that the synchronization and cooperation only happen among the secondary users who belong to the same cluster and no common receiver is needed. In addition, each cluster can select nonidentical sensing time adaptively in accordance to the traffic load and channel gain. As a consequence, the cooperative sensing overhead will be reduced. Besides, because multichannel sensing and access is used, by adapting the transmission power to avoid causing harmful interference, coexistence with the primary user and the transmitting secondary users is made possible. By doing so, the throughput can be improved. Moreover, we explicitly calculate the expected number of channels that are idle, being occupied by the primary users and by the transmitting secondary users. To the best of our knowledge, this is the first work on the topic.

To investigate the performance of the proposed sensing and access method, we have formulated the problem into an optimization problem to improve the achieved throughput and reduce the sensing overhead. Furthermore, quantitative method has been developed to obtain the optimal value for the number of sensed channels, such that the utility can be maximized. The performance of the proposed strategy have been examined quantitatively and is shown to outperform ASA [23] and SSS [24].

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