Adaptive Scheduling of Collaborative Sensing in Cognitive Radio Networks

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***Abstract*—In this paper, we aim to discover more spectrum opportunities in limited sensing delay. We construct a MAC-layer sensing framework for fast discovery of spectrum opportunities. Specifically, we employ the sequential probability ratio test and develop a collaborative sensing scheme for multiuser to collaborate during multi-slot. Moreover, we propose a novel adaptive scheduling of collaborative sensing, in which we effectively utilize the resources of secondary users to sense the channels for fast discovery of spectrum opportunities. Subsequently, we maximize the sum of channels available probability to fast discover the spectrum opportunities, and give an effective heuristic solution based on probability table, which has a low complexity. Simulation results show that the proposed scheme could offer good performance with fast discovery of spectrum opportunities.**

I. Introduction

The current communication systems are characterized by a static spectrum allocation policy according to the spectrum allocation bodies around the world, and few spectrum resources are currently available for future wireless applications. However, a survey shows that the current spectrum utilization is much inefficient [1]. Recently, dynamic spectrum access (DSA) and cognitive radio have been proposed and obtained more and more attention for the growing needs of improving spectrum utilization [2], [3], [4]. The cognitive radio networks (CRN) requires the enhancement of current PHY and MAC protocols to adopt spectrum-agile features which is to allow secondary users (SUs) to access the licensed spectrum band when the primary users (PUs) are absence. Therefore, spectrum sensing for discovering the availability of the licensed spectrum band is commonly recognized as one of the most fundamental elements in CRN.

Spectrum sensing could be realized as a two-layer mechanism. On the one hand, the PHY-layer sensing focuses on efficiently detecting the signals of PUs to identify whether the PUs are present or not [5]. Some PHY-layer sensing methods have been studied including energy detection, matched filter and feature detection. On the other hand, the MAC-layer sensing, which plays an important role in CRN, determines when SUs should sense which channels to obtain good performances, such as sensing delay, throughput of SUs, and so on. The sensing delay results in the performances degradation of secondary users, especially in wideband communication systems since more sensing time is needed to discover enough spectrum opportunities. Therefore, it is an important issue in MAC-layer sensing that how to discover more spectrum opportunities quickly. In [6], the authors adaptively schedule the spectrum sensing periods so that negative impacts to the performance of the CR network are minimized. In [7], the authors study the problem of designing the sensing duration to maximize the achievable throughput for the secondary network under the constraint that the primary users are sufficiently protected. In [8], the authors maximized the overall discovery of opportunities in the licensed channels via the sensing-period optimization, and minimized the delay in locating an idle channel via the optimal channel sequencing algorithm. In [9], we construct a novel MAC-layer sensing framework for fast discovery of spectrum opportunities. In the framework, we employ the sequential probability ratio test (SPRT) and develop a new collaborative sensing scheme for multiuser to collaborate during multi-slot, and propose an adaptive scheduling of collaborative sensing scheme. Different from [9], in this paper, we maximize the sum of channels available probability to fast discover the spectrum opportunities.

The rest of the paper is organized as follows: In Section II, the assumptions and system model are given. Then, the proposed adaptive scheduling of collaborative sensing is presented in Section III. We evaluate the proposed scheme via some numerical results in Section IV and conclude this paper in Section V.

II. System Model

The scenario considered in this paper is illustrated in Fig. 1. We use the concept of cognitive cell, which consists of a cognitive base station (CBS) and a group of M SUs. In the range of cognitive cell, the CBS could effectively receive the data from SUs and schedule SUs for spectrum sensing. We only consider the collaborative sensing among all SUs in this paper. In practice, the role of these collaborative SUs can also be replaced by sensor networks. The licensed spectrum band is equally divided into N nonoverlapping narrowband data channels, and all channels are under Rayleigh fading. The goal

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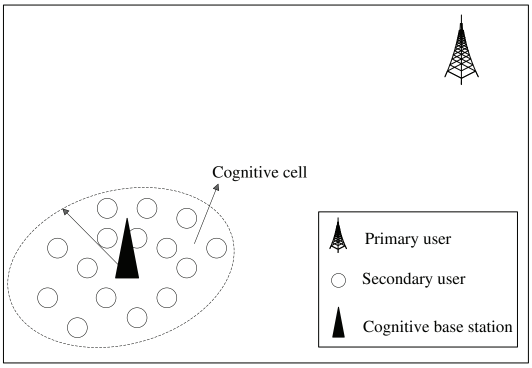

Fig. 1. The considered scenario.

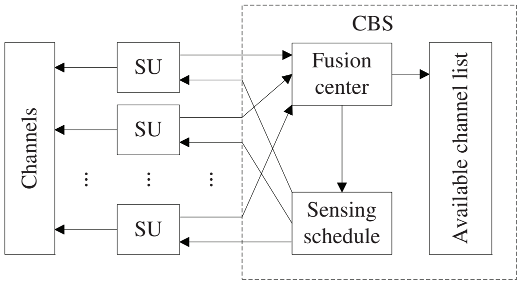

Fig. 2. The system model.

of spectrum sensing is to decide between the following two hypotheses:

$$x_{ij}(t) = \begin{cases} v_i(t), & H_{i0} \\ h_{ij} \cdot s_i(t) + v_{ij}(t), & H_{i1} \end{cases} \tag{1}$$

where $x_{ij}(t)$ is the signal received by the j-th SU in the i-th narrowband, and $i = 1, 2, \cdots, N$, $j = 1, 2, \cdots, M$. $s_i(t)$ is the primary user's transmitted signal in the i-th narrowband which is assumed with mean zero and variance σ_{is}^2, $v_{ij}(t)$ is the complex additive white Gaussian noise (AWGN) with mean zero and variance σ_{ijv}^2, h_{ij} is the instantaneous channel gain between the primary user in the i-th narrowband and the j-th SU. For mathematical brevity, we assume that $\sigma_{is}^2 = \sigma_s^2$ and $\sigma_{ijv}^2 = \sigma_v^2$ for $i = 1, 2, \cdots, N$, $j = 1, 2, \cdots, M$. Moreover, when the distance between PU and SUs is far greater than the distance between CBS and SUs, as illustrated in Fig. 1, it is considered that $h_{ij} = h_j$ for $i = 1, 2, \cdots, N$. Obviously, all these assumptions are reasonable when we consider that the licensed spectrum bands locate in the downlink bands of cellular system or the TV and broadcasting bands. In addition, H_{i0} is null hypothesis, which represents that the primary user is inactive in the i-th narrowband. H_{i1} is the alternative hypothesis, which represents that the primary user is active in the i-th narrowband.

We employ energy detector in each SU to determine whether the primary user is active or not, which is a simple and effective method for the detection of unknown signals. Then, $t_{ij} = \frac{1}{S}\sum_{s=1}^{S} |x_{ij}(s)|^2$ is defined as one observation from the j-SU on the channel i and S is the number of samples. Although t_{ij} has a chi-square distribution [10], according to the central limit theorem, t_{ij} is asymptotically normally distributed if S is large enough ($S \geqslant 20$ is often sufficient in practice) [11]. Specifically, for large S, we can model the statistic of t_{ij} as follows for analytical simplicity:

$$t_{ij} \sim \begin{cases} \mathrm{N}\left(\sigma_v^2, \frac{\sigma_v^4}{S}\right), & H_{i0} \\ \mathrm{N}\left(\sigma_v^2(1+\gamma_j), \frac{\sigma_v^4(1+2\gamma_j)}{S}\right), & H_{i1} \end{cases} \tag{2}$$

where $\gamma_j = \frac{h_j^2 \sigma_s^2}{\sigma_v^2}$ is the received signal-noise-ratio (SNR) of the j-th SU.

We employ slotted-based sensing method in our scheme. One SU could provide one observation on a certain channel in each slot, i.e., the number of observations is equal to the number of SUs in each slot. The system model is illustrated in Fig. 2. The CBS consists of three modules: fusion center, sensing schedule module, and available channel list. The fusion center obtains all the observations from SUs and determines the states of channels, then the idle channels are added to the available channel list, the busy channels are dropped, and the sensing results of the other channels that need more observations are fed into the sensing schedule module. After the proposed schedule algorithm, the sensing schedule module employs the SUs to sense appropriate channels in next slot.

III. The Adaptive Scheduling of Collaborative Sensing

In this section, the details of our proposed scheme are given. First, the basic idea of the proposed scheme is briefly illustrated. Then, after introducing the details of the collaboration based on SPRT method, we propose the adaptive scheduling of collaborative sensing and formulate the problem as an optimization problem.

A. Basic Idea

To reduce the sensing time while keeping the performances of P_{fa} and P_m, that is, keeping the number of observations, we consider a novel adaptive scheduling of collaborative sensing based on multiuser multi-slot SPRT method in the CBS. Fig. 3 is a schematic diagram to illustrate the basic idea of the proposed scheme. In Fig. 4, the number in the box means the number of SUs that we assign to sense a certain channel in a certain slot. When no collaboration is adopted, only one observation on a certain channel is obtained in one slot, which is shown in Fig. 3(a), and until the Δ-th slot, only one channel's state is determined. The conventional collaboration is shown in Fig. 3(b), all SUs (in this schematic diagram, we assume the number of SUs $M = 9$) sense one channel in one slot, i.e., M observations on a certain channel are obtained in one slot, and until the Δ-th slot, four channels' states are determined. When the number of SUs is large, some observations from SUs may be wasted in conventional collaboration scheme since only a part of observations are needed to determine the channel state with certain P_{fa} and

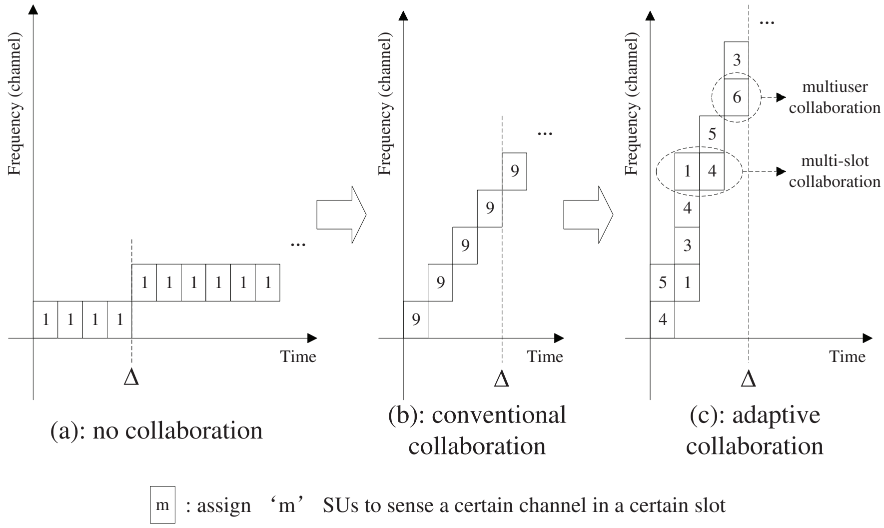

Fig. 3. The basic idea of the proposed scheme.

P_d guarantee. To solve this problem, we propose the proposed scheme which is shown in Fig. 3(c). Appropriate number of observations on a certain channel are obtained in one slot, and thus more than one channel's state would be determined in one slot. From the Fig. 3(c), eight channels's states are determined until the Δ-th slot. Obviously, the key issue to be solved is that how many SUs should collaborate to detect the signals on the channel i in each slot, $i = 1, \cdots, N$, i.e., effective sensing scheduling algorithm should be investigated. Before the introduction of the proposed algorithm, some details of the collaboration based on SPRT are introduced in the following subsection.

B. Collaboration based on SPRT

In the current slot, we assume each SU observes a certain channel and obtain one observation on this channel. All observations are assumed to be independent and identical distributed (i.i.d.). Let $\mathbf{t}_i = [t_{i1}\ t_{i2}\ \cdots\ t_{iU_i}]$ denote the observations on the channel i, where U_i is the number of observations (i.e., the number of SUs that sense the channel i), $0 \leqslant U_i \leqslant M$, $i = 1, \cdots, N$ and $\sum_{i=1}^{N} U_i = M$. The likelihood ratio of $\mathbf{t}_i$ is given by:

$$\Lambda(\mathbf{t}_i) = \prod_{k=1}^{U_i} \Lambda(t_{ik}) = \prod_{k=1}^{U_i} \frac{f(t_{ik}|H_{i1})}{f(t_{ik}|H_{i0})}. \tag{3}$$

For simplified analysis, we use log-likelihood ratio (LLR) in this paper. The LLR of $\Lambda(\mathbf{t}_i)$ is obtained as:

$$L(\mathbf{t}_i) = \ln \Lambda(\mathbf{t}_i) = \sum_{k=1}^{U_i} \ln \Lambda(t_{ik}) = \sum_{k=1}^{U_i} L(t_{ik}), \tag{4}$$

where $L(t_{ik})$ is the LLR of the k-th observation on the i-th channel in current slot. If T_{ik} denotes the statistic of $L(t_{ik})$, we have (the proof is omitted due to limited space):

$$T_{ik} \sim \begin{cases} \chi_1^2\left(s_{0i}^2\right) + const, & H_{i0} \\ \chi_1^2\left(s_{1i}^2\right) + const, & H_{i1} \end{cases} \tag{5}$$

where s_{0i}^2 and s_{1i}^2 is the non-central parameters under H_{i0} and H_{i1}, respectively.

Then, the LLRs of observations from all SUs are transmitted to the fusion center, and decisions about the spectrum opportunities are made via SPRT method. The decision rule for the SPRT with thresholds η_0 and η_1, denoted by $SPRT(\eta_0, \eta_1)$, is given by:

$$\begin{cases} L(\mathbf{t}_i) \geqslant \ln \eta_1, & \text{accept } H_{i1} \\ L(\mathbf{t}_i) \leqslant \ln \eta_0, & \text{accept } H_{i0} \\ \ln \eta_1 \geqslant L(\mathbf{t}_i) \geqslant \ln \eta_0, & \text{taking another observation} \end{cases} \tag{6}$$

The following properties of the SPRT is well-known in [12].

Theorem 1: Let $P_m = \alpha$ and $P_{fa} = \beta$ be the probabilities associated with $SPRT(\eta_0, \eta_1)$, then the two thresholds η_0, η_1 satisfy:

$$\eta_1 \leqslant \tfrac{1-\alpha}{\beta}, \quad \eta_0 \geqslant \tfrac{\alpha}{1-\beta} \tag{7}$$

when a decision to accept H_{i1} or H_{i0} is made, if the LLR is exactly equal to the corresponding threshold, which happens if the LLR is a continuous process, the above inequalities become equalities. In practice, we usually employ the equalities, and have the following theorem:

Theorem 2: Let $\eta_1 = \frac{1-\alpha}{\beta}$ and $\eta_0 = \frac{\alpha}{1-\beta}$. Let α^* denote the practical miss detection probability and β^* denote the practical false alarm probability. Then, if $\alpha + \beta < 1$, we have:

$$\alpha^* \leqslant \tfrac{\alpha}{1-\beta}, \quad \beta^* \leqslant \tfrac{\beta}{1-\alpha} \tag{8}$$

C. Problem Formulation

To fast discover available channels, we hope to assign appropriate number of SUs to sense channels in each slot. We formulate the problem as follows:

$$\max_{\mathbf{U}} \left\{ \sum_{i=1}^{N} G_i(U_i, i) \right\} \quad s.t. \begin{cases} \sum_{i=1}^{N} U_i \leqslant M \\ 0 \leqslant U_i \leqslant M \end{cases}, \tag{9}$$

where $\mathbf{U} = [U_1, \cdots, U_i, \cdots, U_N]$, $G_i(U_i, i)$ is the available probability of channel i when U_i SUs sense channel i. Based on (5), $G_i(U_i, i)$ can be obtained by:

$$G_i(U_i, i) = \begin{cases} P\left(\sum_{k=1}^{U_i} T_{ik} < \ln \eta_0 - \xi_i\right), & U_i > 0 \\ 0, & U_i = 0 \end{cases} \tag{10}$$

where ξ_i denotes the LLR of the observations until the current slot on the channel i, and $P\left(\sum_{k=1}^{U_i} T_{ik} < \ln \eta_0 - \xi_i\right)$, the deduce of which is omitted due to the limited space, is the available probability of channel i when U_i SUs are assigned to sense channel i in the current slot, $i = 1, \cdots, N$.

It is obvious that this is a finite state variables optimization problem. The optimal solution would be obtained when N^M possible $\mathbf{U}$ that satisfy (9) are searched, which has huge complexity. Therefore, we investigate an effective heuristic algorithm to obtain the solution based on probability table. First, we randomly select one SU and calculate N channel available probabilities when the SU is assigned to sense the N corresponding channels. Second, we assign this SU to the channel with the largest available probability. Then we assign the remaining SUs in turn by the similar approach. In the end, all SUs are assigned to channels, and let U_i denote the number of SUs assigned to the channel i, $i = 1, \cdots, N$. The pseudo-code of this effective strategy is given in **Algorithm 1**. In this strategy, we do a total of $N \times M$ operations when $\mathbf{U}$ is found, i.e., the complexity is $O(N \times M)$, which is much lower than brute-force search.

IV. Performances

In this section, we evaluate the proposed scheme with Monte Carlo searching. For all simulations, we consider that the channel number $N = 100$ and each channel is idle with probability $P_a = 0.5$ (i.e., about 50 channels are available), and all the channels are under Rayleigh fading. The SUs are randomly distributed within the coverage radius of the CBS. For comparison, we also consider conventional nonadaptive collaborative scheme. In conventional scheme, all M SUs are assigned to one channel (i.e., $\mathbf{U} = [0 \ \cdots \ M \ \cdots \ 0]$) in each slot for opportunity discovery until the decision is obtained. In the following, we would evaluate the performances of the proposed scheme compared with the conventional scheme. Meanwhile, we investigate the impacts of, SUs number and SNRs on the performances of the proposed scheme.

Fig. 4 shows the performances of the proposed scheme compared with the conventional scheme with the number of SUs $M = 80, 1$ under the average SNR $\gamma = -10$dB, $P_m = P_{fa} = 10^{-2}$. The horizontal axis represents the sensing time, and the vertical axis represents the number of the discovered

Algorithm 1 an effective strategy to solve the optimization problem

Initialization:

for $i = 1 : N$
  $\xi_i = 0$;
end for

Procedure: In each slot, we do

for $i = 1 : N$
  $U_i = 0$;
end for
for $j = 1 : M$
  $G = 0$;
  $index = 0$;
  for $i = 1 : N$
    $G_i = P\left(T_{ij} < \ln \eta_0 - \xi_i\right)$;
    if $G < G_i$
  $G = G_i$;
  $index = i$;
    end if
  end for
  $\xi_{index} = \ln \frac{f(t_{index,j}|H_1)}{f(t_{index,j}|H_0)}$;
  $U_{index} = U_{index} + 1$;
end for

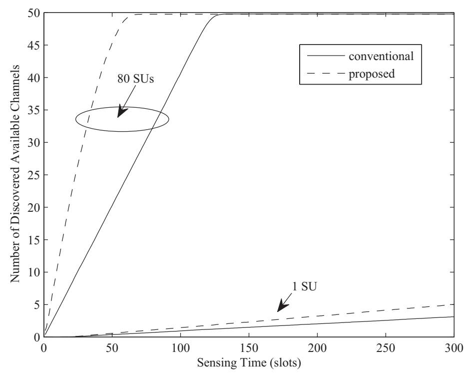

Fig. 4. The performances of conventional and proposed spectrum opportunities discoveries schemes with different number of SUs under the average SNR $\gamma = -10dB$, $P_m = P_{fa} = 10^{-2}$.

available channels. It is obvious that the proposed scheme with different number of SUs could discover the available channels faster than the conventional scheme. In addition, it is necessary to explain the simulation result when $M = 1$. In this situation, the proposed scheme also outperforms the conventional scheme, since we always sense the best channel that is available with highest probability in proposed scheme, and sense a fixed channel without considering the available probability until the channel is determined as idle or busy in conventional scheme.

To further evaluate performances of the schemes under different SNRs, we obtain the sensing time when 30 available channels are discovered, which is illustrated in Fig. 5. In

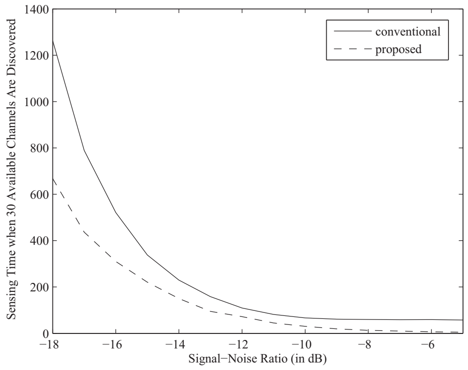

Fig. 5. The average sensing time versus different SNRs, 30 available channels are discovered, $M = 80$.

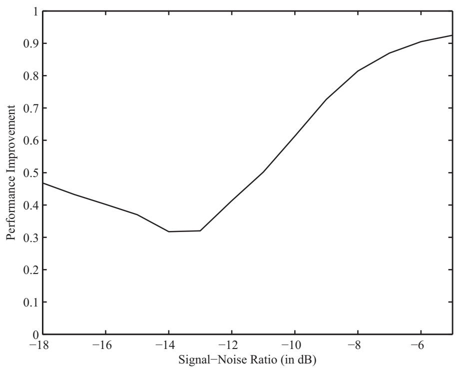

Fig. 6. Performance improvement versus different SNRs, 30 available channels are discovered, $M = 80$.

this figure, the horizontal axis represents the different SNRs, and the vertical axis represents the sensing time when 30 available channels are discovered. It is obvious that the proposed scheme outperforms the conventional scheme under all SNRs. In addition, when SNR is higher than -9.0dB, the sensing time of the conventional scheme would not reduce as SNR increases. On the contrary, the sensing time of the proposed scheme would reduce with the increase of the SNR. This is easy to understand. When SNR is higher, no more than one idle channel would be discovered in one slot in conventional scheme. However, more than one idle channel would be discovered in one slot in the proposed scheme since more than one channel is detected in one slot.

In addition, we define the performance improvement as $\rho = \frac{SensingTime1 - SensingTime2}{SensingTime1}$, where $SensingTime1$ and $SensingTime2$ are the sensing time of the conventional scheme and proposed scheme, respectively, when 30 available channels are discovered. Fig. 6 shows the performance of ρ versus different SNRs. Under higher SNRs, the proposed scheme has more performance improvement compared with the conventional scheme. When SNR is about -13.5dB, the performance of the proposed scheme is close to that of the conventional scheme since $\sum_{i=1}^{N} G_i$ under the proposed assignment vector $\mathbf{U}$ is chose to that under $\mathbf{U} = [0 \ \cdots \ M \ \cdots \ 0]$. Therefore, ρ has the smallest value. Under lower SNRs, the performance of the conventional scheme reduces rapidly. However, the performance of the proposed scheme reduces more slowly than the conventional scheme since the property of adaptive scheduling, which is also shown in Fig. 5. Hence, the performance improvement of the proposed scheme is also obvious under lower SNRs.

V. Conclusions

In this paper, we constructed a novel MAC-layer sensing framework for fast discovery of spectrum opportunities. Specifically, we employed the sequential probability ratio test and developed a new collaborative sensing scheme for multiuser to collaborate during multi-slot. Moreover, we proposed an adaptive scheduling of collaborative sensing, in which we effectively utilized the resources of secondary users to sense the channels for fast discovery of spectrum opportunities. Subsequently, we maximized the sum of channels available probability to fast discover the spectrum opportunities, and obtained an effective heuristic solution based on probability table, which has a low complexity. Simulation results show that the proposed scheme could offer good performance with fast discovery of spectrum opportunities.

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