Prioritized Spectrum Sensing Scheme Based on Semi-Markov Process

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Abstract— **In this paper, a novel MAC-layer spectrum sensing scheme base on continuous-time semi-Markov process is investigated for the purpose of improving spectrum sensing efficiency of cognitive radio (CR) systems. The scheme focuses on identification of the optimal sensing sequence of channel by modeling a group of licensed channels' usage pattern as a continuous-time semi-Markov process. Simulation results show that the proposed algorithm has the potential to achieve noticeably improved performance in terms of reduction the sensing overhead and second user's average throughput when compared to the conventional non-prioritization spectrum sensing approach, thus is suitable for CR networks.**

I. Introduction

Cognitive radio systems [1] present the opportunities to improve spectrum utilization by detecting unoccupied portions of licensed spectrum such as TV bands or cellular bands and allowing secondary users (SUs) to use them. Hence, spectrum sensing has to be performed by the SU in order not to harmfully interfere with primary users (PUs). Spectrum sensing can be realized as a two-layer mechanism [2]. The PHY-layer sensing focuses on efficiently detecting PU signals to identify opportunities. Spectrum sensing techniques have been explored, such as energy detection, match filter detection and cyclostationary feature detection [3]. On the other hand, the MAC-layer sensing determines when SUs have to sense which channels. There are two important issues of the MAC-layer sensing: 1) how to minimize the delay in locating an idle channel in a secondary network; 2)how to minimize the number of spectrum handover. The spectrum handover occurs when a secondary user has to change its spectrum access due to the arrival of a primary user. To obtain more efficient MAC-layer sensing scheme, the history information of the spectrum usage can be used for predicting the future profile of the spectrum usage [3]. In fact, the SUs can remarkably mitigate the sensing time by predicting spectrum holes and adopting the best strategy of selecting channels for sensing and access.

There are numbers of previous works which considered the channel selection in spectrum sensing in CR networks. For example, recent non-cooperative spectrum sensing algorithms in [4]-[6] assumed primary user's behavior as an ON/OFF exponential traffic model. Based on this simplification, the distributions of both busy and idle periods were exponentially-distributed. In [7] hidden Markov model was used to predict the spectrum hole. It assumed that each primary user had a unique Poisson distributed spectrum usage pattern. [8] proposed a dynamic spectrum access scheme based on MAC-Layer spectrum sensing and a prior channel pre-allocation strategy. [9] proposed an optimal access strategy in which the transmissions of primary users were modeled as independent continuous-time Markovian on-off processes. In [10], the author proposed a simple channel sensing order for secondary users in multi-channel CRNs without a priori knowledge of primary user activities. The previous researches [4]-[9] only depend on the call arrival and call duration distributions, which were both assumed to be exponential. Although such an assumption has brought convenience in the theoretic analysis, in fact that it is not appropriate to cellular band [11]. In [11], the primary user behavior in cellular networks was investigated where they presented the results of a large-scale measurement-driven study of PUs. The results showed significant deviations of call durations from exponential distributions.

In this work, we focus on a more practical cellular system. Based on the previous observation, it's not precise to model the cellular primary user's behavior pattern as a continuous-time Markov chain(CTMC). Therefore, we consider to model the cellular primary user's behavior pattern as a semi-Markov model to allow for specifying the occupancy periods for each state arbitrarily not exponentially as in a CTMC. We will propose a prioritized spectrum sensing scheme based on modeling a group of licensed channels' usage pattern as a continuous-time semi-Markov process. Meanwhile, the relativity between different channels is also considered. Based on this model, we combine channel utilization with channel state transition probability from idle to busy to reflect the channel opportunity quality of cognitive radio systems. Then we particularly focus on identification of the optimal sequence of available channels and find which channel is the best choice to be sensed to improve the sensing efficiency and quality of SU's transmission.

The rest of this paper is organized as follows.The system model is presented in II. The proposed prioritized spectrum sensing algorithm is described in Section III. Numerical results are discussed in Section IV. Finally, conclusions are drawn in Section V.

II. System Model

We consider a centralized CR system with of a cognitive base station (CBS) and N SUs under the coverage of the

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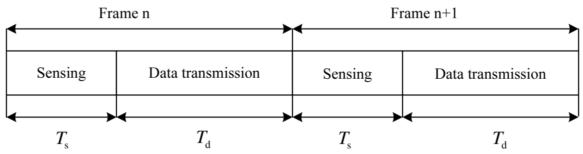

Fig. 1. Frame structure of the second user

CBS. The entire spectrum of interest is divided into *M* disjoint narrow channels, which can be indexed with $i = 1, 2, \cdots, M$. A licensed channel i can be used by SUs when it is not occupied by PU. For each SU, the procedure includes *sensing period* and *data transmission period*. The frame structure consisting of a sensing time slot and a data transmission slot is depicted in Fig.1 [12]. We assume that the sensing period T_s of SU is more less than the sojourn time of primary use. SU could find out the spectrum holes to access during the sensing periods. As long as the SU obtains an available channel, the SU could transmit at the next data transmission time slot. During the *data transmission period*, SU should pause its current transmission when PU is detected on the current channel. The SUs are synchronized so that they sense the channel in unified sensing slots and report their respective binary sensing results to the CBS. CBS could collect the sensing information from the local sensing results at SUs and fuse the information to get the final PU occupancy decisions for the channel. On one hand, CBS obtains the occupancy status of the entire channels of interest in every sensing slot (usually very short) to learn the usage pattern of PU which can be used for predicting the future spectrum usage. On the other hand, CBS provides statistical information of the channels for SU.

The SU receives the statistical of the channel usage information from CBS and obtains the sequence of spectrum sensing based on the proposed prioritized spectrum sensing algorithm. After that, the SU performs sensing according to the sequence. Upon the identification of any available channel, the SU could access immediately. Otherwise, they will update the sequence of sensing and continue sensing. In this way, the sensing period can be alleviated. A flowchart summarizing the prioritization process is shown in Fig.2.

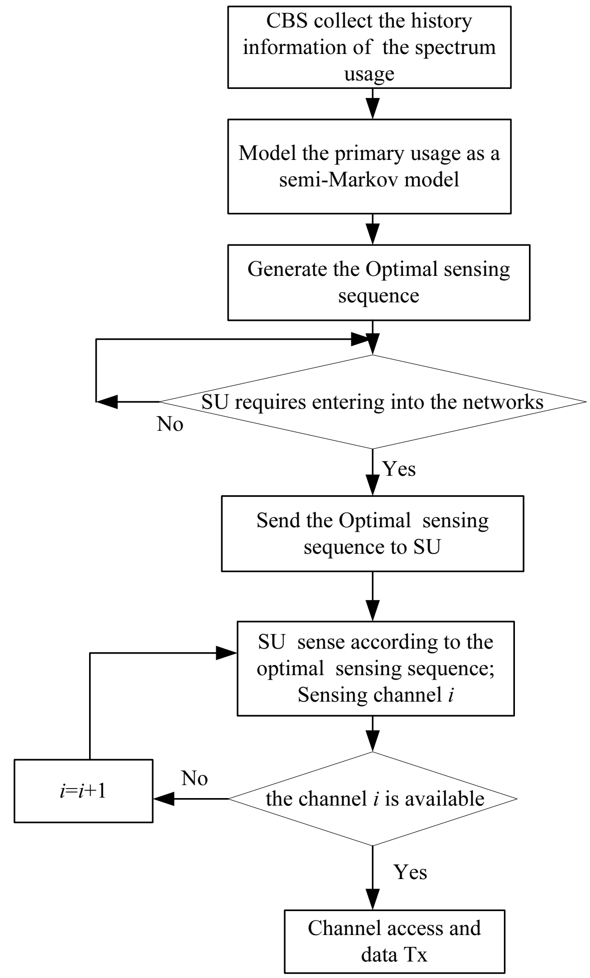

Fig. 2. Flowchart of the prioritization process

III. PROPOSED ALGORITHM FOR SENSING

The section introduces our approach based on semi-Markov process for dynamic spectrum sensing. We particularly focus on identification of the sequence of available channels via a prediction approach, so as to achieve better opportunity in channel access.

A. Problem Formulation

Let $\{\mathbf{CH}|CH_i, i = 1, \cdots, M\}$. Let T be a sequence of time instances and $t \in T$. Let $s_{t,i}$ denotes selecting channel i for sensing at time t. Furthermore, let $X_{s_{t,j}}$ be a binary random variable representing the channel availability of $s_{t,j}$, which takes a value of 1 if the channel is available and 0 otherwise. Let $P\{X_{s_{t,i}} = 0\}$ denotes that SUs fail to obtain an available channel. For mitigating the sensing time and number of spectrum handover, we need find the channel with the maximal probability of available and then sense it firstly. Hence, the problem of selecting the best channels for sensing can be formulated as follows:

$$\arg\max_{i \in \mathbf{CH}} \{P\{X_{s_{t,i}} = 1\}\} \tag{1}$$

Define p_i as the occupied probability of CH_i. Statistically, secondary user more likely obtains the available channel when it senses the channel with lower probability of occupation. Based on the above analysis, we have an expression as follows:

$$\arg\max_{i \in \mathbf{CH}} \{P\{X_{s_{t,i}} = 1\}\} \approx \arg\min_{i \in \mathbf{CH}} \{p_i\} \tag{2}$$

Note that directly obtain the solution for (1) is difficult, while $\arg\min\{p_i\}$ can be obtained by our proposed algorithm based on semi-Morkov process.

B. Introduction of Semi-Markov process

As mentioned above, the CTMP is not accurate enough for describing the characteristic of behavior of cellular primary users. To tackle the problem, a semi-Markov process is introduced. Semi-Markov process is a stochastic process whose transition behavior can be characterized in two steps [13]. First, the transition between states follow a Markov chain which is called embedded chain. The embedded chain is specified by a transition matrix $\mathbf{P}$.

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{bmatrix}$$

where p_{ij} denotes the probability that a transition from state i to state j occurs. Secondly, given that the system is in state i and will transit to state j, the sojourn time t in state i is distributed according to cumulative distribution function $F_{ij}(t)$. Note that $p_{ii} = 0$ for all i because the arbitrary specification of the sojourn time fully captures the time spent in each state.

C. Proposed algorithm

According to the history of the spectrum usage information, the M non-overlapping channels can be sub-divided into m subsets. In each subset, the probability that more than one channel is occupied at one time is infinitesimal of higher order. Let $M^{(i)}$ denotes the channel number of *i*th subset, then

$$M = \sum_{i=1}^{m} M^{(i)} \tag{3}$$

Note that the number of element in different subset can be different. Consider *i*th subset which contains $M^{(i)}$ channels. Define $n_i = 1, \cdots, M^{(i)}$ and state n_i represents that channel n within the *i*th subset is occupied by PU. Furthermore, let state IDLE denotes none of channels within the subset are occupied by PU. Let $Z^i(t)$ denotes the state of *i*th channel subset at time t. Then,$\{Z^i(t), t \geq 0\}$ becomes a semi-Markov Process with $M^{(i)} + 1$ states. Given unbroken chain of observations, we can use well-known maximum-likelihood techniques to obtain estimates for the transition probability matrix. In particular, we have the following estimator

$$\hat{p}_{ij} = \frac{n_{ij}}{n_j} \tag{4}$$

where the $\hat{p}_{ij}$ denotes the estimated value transition probability p_{ij} and the transition count n_{ij} is the number of transitions $i \longrightarrow j$ occuring in our historical observation period. Similarly, $n_i = \sum_k n_{ik}$ denotes the number of times that the system resides in state i.

We can obtain the *i*th semi-Markov process's embedded chain transition probability based on the semi-Markov model mentioned above. The transition probability is given as follows.

$$p_{ij} = \begin{cases} 0, & i, j \neq M^{(i)} + 1 \\ 1, & j = M^{(i)} + 1 \\ \hat{p}_{ij}, & i = M^{(i)} + 1 \\ 0, & i = j \end{cases} \tag{5}$$

Then, according to (5), the *i*th semi-Markov process's embedded chain transition matrix defined as $\mathbf{P}_i$:

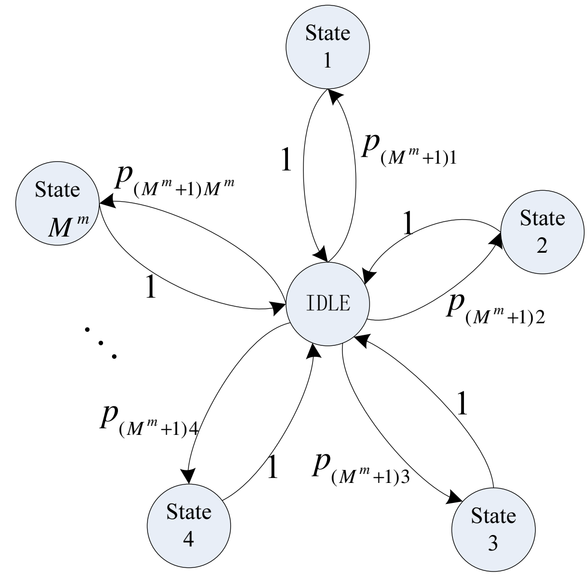

Fig. 3. State transition diagram of proposed model

$$\mathbf{P}_i = \begin{bmatrix} 0 & \cdots & 0 & 1 \\ 0 & \cdots & 0 & 1 \\ \cdots & \cdots & \cdots & 1 \\ 0 & \cdots & 0 & 1 \\ P_{(M^i+1)1} & \cdots & P_{(M^i+1)M^i} & 0 \end{bmatrix}_{(M^i+1)\times(M^i+1)}$$

where the $P_{(M^{(i)}+1)i}, i = 1, \cdots, M^i$ denotes the probability that a transition from state IDLE to state i. The state transition diagram of proposed model is shown in Fig.3 according to the transition matrix.

According to the state transition diagram shown as Fig.3, the embedded chain is positive recurrent and irreducible. Let $\tau_j^{(k)}$ denotes the sojourn time in state j at *k*th time. $N_j^{(n)}$ denotes the number state j occuring in previous *n*th transition. Furthermore, let $p_j^{(n)}$ denotes the time proportion of state j in previous *n*th transition. According to (6) and strong law of large numbers, the $p_j^{(n)}$ is given by (8)

$$\pi_j = \lim_{n \to \infty} p_j^{(n)} \tag{6}$$

$$p_j^{(n)} = \frac{\sum\limits_{k=1}^{N_j^{(n)}} \tau_j^{(k)}}{\sum\limits_i \sum \tau_i^{(k)}} = \frac{\frac{N_j^{(n)}}{n} \frac{1}{N_j^{(n)}} \sum\limits_{k=1}^{N_j^{(n)}} \tau_j^{(k)}}{\sum\limits_i \frac{N_i^{(n)}}{n} \frac{1}{N_i^{(n)}} \sum\limits_{k=1}^{N_i^{(n)}} \tau_i^{(k)}} \tag{7}$$

$$\overset{n\to\infty}{=\!\!\longrightarrow} \frac{\tilde{\pi}_j E\tau_j}{\sum\limits_i \tilde{\pi}_i E\tau_i} \tag{8}$$

where the $\tilde{\pi}_i$ denotes the stationary distribution of the embody chain and $\mathbf{E}\tau_j$ presents the expectation of the sojourn time in state j. Then, we can obtain the *i*th semi-Markov process's limit distribution $\{\pi^i|\pi^i_j, j = 1, \cdots, M^{(i)} + 1\}$. As defined, $\pi^i_{M^{(i)}+1}$ denotes the limit probability of the state OFF (IDLE) periods.

The rest may be deduced by analogy. Hence, we obtain m semi-Markov process since the entire spectrum of interest is divided into m subset.

Then, a question is which channel subset should be assigned to SU firstly? To tackle this problem, we introduce *Discrepancy Index*, which denotes channel usage ratio difference within one channel subset. *Discrepancy Index* of *i*th channel subset is expressed as follows:

$$S_i = \frac{1}{\mathrm{C}^2_{\mathrm{M^{(i)}}}} \sum_{m=1}^{M^{(i)}-1} \sum_{n=m+1}^{M^{(i)}} [(\pi^i_m - \pi^i_n) - \overline{\pi_i}]^2 \tag{9}$$

where the $\overline{\pi_i}$ denote the mean difference between π^i_n and π^i_m,$m, n \in 1, \cdots, M^{(i)}$

$$\overline{\pi_i} = \frac{1}{\mathrm{C}^2_{\mathrm{M^{(i)}}}} \sum_{m=1}^{M^{(i)}-1} \sum_{n=m+1}^{M^{(i)}} (\pi^i_m - \pi^i_n) \tag{10}$$

As the difference between $\pi^i_m - \pi^i_n$ and $\overline{\pi_i}$ becomes smaller, *Discrepancy Index* gradually gets closer to zero, indicating the channel usage ratio of the channel subset is equal. Assume a secondary user's request for a session requires a time length of T. In order to quickly locate an available channel and reduce unnecessary handovers, a channel subset with larger *Discrepancy Index* is needed.

A detailed expression of the sensing scheme is given as follows.

Step1: According to the history of the spectrum usage information, the CBS obtains m subsets of the entire spectrum of interest.

Step2: CBS calculates overall semi-Markov process's limit distribution according the (8), where $\pi = \{\pi^i_j, j = 1, \cdots, M^i + 1\}$.

Step3: CBS calculates the *Discrepancy Index* for each subset by (9). CBS descends all *Discrepancy Index* and then assign the channel subset with maximum *Discrepancy Index* to SU.

Step4: Upon the information of assigned channel subset, the SU sorts channel limit probability by value and then search channels in descending order of limit probability π^i_j. Upon the identification of any available channel, the available channel is accessed by the secondary users immediately. If fail to locate an available channel, SU would request CBS to assign a new channel subset and upload the channel message to CBS.

IV. SIMULATION RESULTS

To evaluate the effectiveness of the proposed spectrum sensing algorithm, simulations are conducted to compare the proposed approach with the traditional non-prioritization approach. The performance measurements are defined as follows:

1) Sensing overhead o: the ratio of total time consumed on spectrum sensing to the data transmission time.

TABLE I
SYSTEM PARAMETERS

Sensing period, T_s	10ms
Data transmission period, T_d	90ms
Length of SU's frame	100ms
SU's data transmission rate, R	$500kb/s$
Shape parameter, α	0.01
Threshold parameter, β	5
Mean of vacant duration, λ_{idle}	0.5sec
Mean of PU's call duration, λ_{busy}	10min

2) Throughput : the ratio of data packet (frame) length to the overall process time, i.e., the amount of data bits transmitted every second.

In the simulations, 10 channels are considered exist in the licensed spectrum, which can be divided into 1 subsets according to proposed rule and can easily be extended to multi-channel subset environment. To verify the adaptability of the proposed scheme, we observed the performance of proposed scheme under different randomly generated the call duration of primary user occupies patterns at first, including: i) exponential working time with an average time of $\lambda = 10min$ and ii) Pareto working time with a Pareto distribution with shape parameter as 0.01 and threshold parameter as 5. Meanwhile, the vacant duration of licensed spectrum is assumed to be exponentially-distributed according to [11]. We randomly generate the time when the SU starts sensing the channel. We assume that the data in the current frame of SU can be transmitted successfully as long as the SU senses and accesses the available channel in the sensing period. Furthermore, the scenarios are designed with the call duration of SU range from 300 *sec* to 700 *sec*. System parameters are listed in Table I. The proposed scheme and non-prioritized scheme are run separately in every scenario. In each scenario, we statistically calculates the probability of successful access during 5000 realizations and average the value by running the process 50 times. The comparison is made between the overall performance of sensing overhead and average throughput.

A. Sensing overhead

To investigate the trade-off between the projected data transmission rate and sensing time, we compare the sensing overhead of the proposed scheme with the sensing overhead of the non-prioritized approach. In Fig.4, the statistics pertaining to the sensing overhead o for both the proposed scheme and the non-prioritized approach are plotted. It can be seen that the average sensing overhead of the proposed approach is noticeably lower than that achieved by the non-prioritized approach. The sensing overhead increase When the call duration of the SU increasing, Furthermore, Fig.4 shows that the performance of the proposed scheme remains consistent when the call duration of PU occupies obeys Non-exponential distribution.

B. Throughput

To investigate the ratio of data packet (frame) length to the overall process time, we compare the sensing overhead of

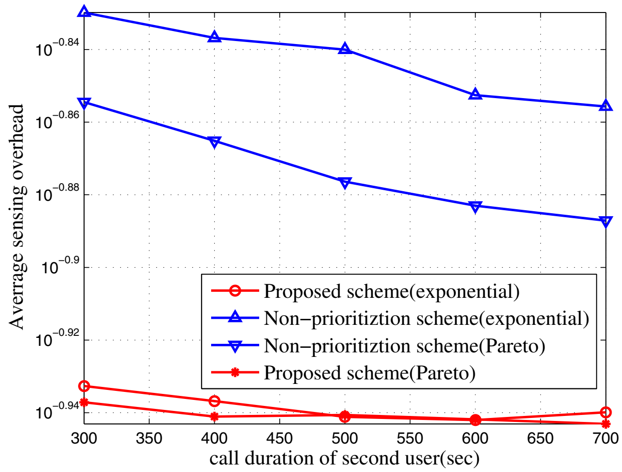

Fig. 4. Simulation results of sensing overhead in comparison

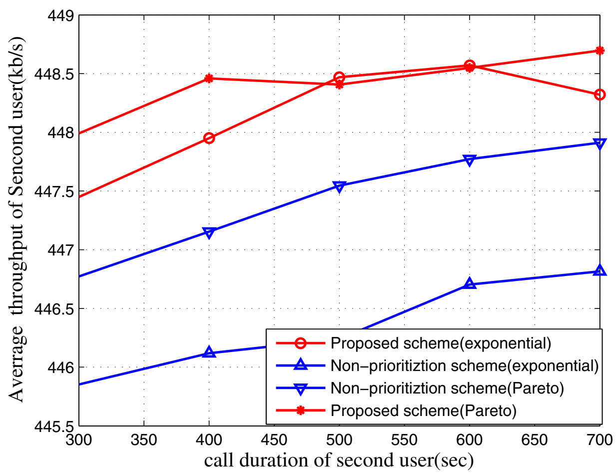

Fig. 5. Simulation results of average throughput in comparison

the proposed scheme with the sensing overhead of the non-prioritized approach. We assume that data transmission rate is 500kbps. Fig.5 shows comparison of average throughput between the proposed scheme and non-prioritized scheme. It can be observed that the overall average throughput is significantly higher for proposed scheme than the non-prioritized approach.

C. simulation summary

As shown in the Fig.4 and Fig.5, the performance of the proposed approach remains consistent under the different parameters while the performance of the non-prioritization approach is much more sensitive to the variation of parameter. The improved performance stems from its ability of better capturing the channel with higher quality for sensing and access.

V. CONCLUSION

In this paper, we present a novel spectrum sensing scheme based on a semi-Markov model. Simulations were conducted to validate the proposed scheme and compare the proposed scheme with non-prioritized in terms of sensing overhead and throughput. Experimental results demonstrated that the proposed scheme can achieve better sensitivity in the presence of traffic variation noticeably due to the adaptability of model - a desired feature for spectrum sensing schemes in the future dynamic CR networks.

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