Cognitive Access in Multichannel Wireless Networks using Two-Dimension Markov Chain

Han-Feng Lin and Shin-Ming Cheng
Department of Computer Science and Information Engineering,
National Taiwan University of Science and Technology,
Taipei 106, Taiwan.
{m10215031, smcheng}@mail.ntust.edu.tw

Po-Yao Huang
Mediatek Inc.,
Hsinchu City 30078, Taiwan.
bernie.huang@mediatek.com

***Abstract*—The cognitive capability of secondary users in multichannel wireless networks enables the functionalities of system parameter estimation and learning, so that a more intelligent channel access without interfering the primary users is possible. This paper proposes a novel cognitive channel access algorithm with threshold policy on the basis of a continuous-time Markov chain built by the estimated parameters. The secondary users could access the channel in a more intelligent fashion and thus the better quality of service can be achieved. The numerical results show that cognitive channel access can significantly increase the total utility of system while keeping blocking probability of primary users' requests under a predefined constraint.**

Keywords-call admission control; continuous-time Markov chain; cognitive radio networks; dynamic channel access

I. Introduction

Cognitive radio (CR) has received a great amount of attentions as a promising technology to enhance spectrum utilization by spectrum sensing and opportunistic access [1]. Unlicensed cognitive users (CUs), also known as secondary users (SUs), adapt their transmissions/receptions to exploit the available channels while spontaneously limiting their interference with licensed primary users (PUs). One way is to strictly prevent CUs from interfering PUs in both time and frequency domains (known as *interweave* paradigm), and the other is to allow interference from CUs while minimizing the affection to PUs (known as *underlay* paradigm) [2], [3].

To achieve the above goal, CUs should determine the available spectrum holes, coordinate access with existing CUs, and release transmission opportunity when PU is active [4]. Primary system typically divides the spectrum into a set of multiple orthogonal logical channels using frequency, timeslot, code, or antenna and its polarization state of multi-input multi-output (MIMO). The traditional dynamic spectrum access in multichannel primary system was studied from the perspective of centralized channel allocation with call admission control (CAC) [5], where primary system base station (PS-BS) organizes requests of channel access from PUs and CUs. Futility (including call prohibition and drop) to PUs may occur since PUs blindly make access request to PS-BS for admission. However, CUs with spectrum sensing capability can distributedly estimate and learn system parameters before practically accessing PS-BS. Thus CUs could perform feasible channel access that alleviates futility in an active sense.

The effect of interference to PUs from the perspective of channel allocation is considered as the quality of service (QoS) degradation of PUs. Existing research focuses on providing penalty [6] or compensation [7] to PUs for QoS degradation. However, these may not be suitable since PUs should not be affected by the channel access of CUs. Specifically, the incremental blocking probability of PUs' requests from the presence of CUs should be kept under a given constraint. The key to alleviate active futility of CUs and constrain QoS degradation of PUs lies in the cognitive functionalities of CUs. Via periodical spectrum sensing, the average arrival and service rates of PUs and CUs in primary system can be estimated at CU. A continuous-time Markov chain (CTMC) is built to model the behavior of channel allocation in PS-BS [8]. Therefore, each CU may intelligently make channel access decision considering the impact from CUs' requests on PUs' QoS degradation. We subsequently propose a cognitive channel access (CCA) algorithm where CU determines the access strategy according to the sensing results such that the aggregated utility of PUs and CUs is maximized with a hard constraint on blocking probability of PUs' requests.

The remainder of this paper is organized as follows: In section II, we introduce our system model by using continuous-time Markov chain (CTMC) and provide the algorithm that is the constraint to the access of the CUs. In section III, we provide the numerical results of our proposed system model by using MATLAB. Finally, we conclude the results in section IV.

II. System Model

We consider a PS-BS with multiple channels for multiple access, where PUs can freely access the channels, while CUs sense channels availability, estimate the system parameters of primary system and the current system load, and then make access decision to connect to primary system.

A. Spectrum Sensing and Load Estimation

Various spectrum sensing techniques [1], [9]–[11] can be adopted to detect and identify the existence of PU on a

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channel. The instantaneous channel availability of specific logical channel can thus be determined. Define $1_k(n)$ as the indicator function denoting the availability of k-th channel at time t_n:

$$1_k(n) = \begin{cases} 1, & \text{channel } k \text{ is occupied at } [t_n, t_{n+1}), \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

With the help of spectrum sensing mechanisms [9], [12], [13] that identify instantaneous channel availabilities, the number of users can be estimated in various multiple access systems. For example, in TDMA systems, channel availabilities are $\mathbf{1}(n) = \{1_k(n), \ldots, 1_k(n+t), \ldots, 1_k(n+N-1)\}$, where N is the period in TDMA. In FDMA systems, channel availabilities are $\mathbf{1}'(n) = \{1_0(n), \ldots, 1_k(n), \ldots, 1_{K-1}(n)\}'$, where K is the number of frequency bands. Note that the orthogonal logical channels can be in timeslots, frequency bands, codes, or patterns. Thus the representation is universal and applicable to various systems. The general matrix form of channel availabilities is:

$$\mathbf{I}(n) = \begin{pmatrix} 1_0(n) & \cdots & 1_0(n+N-1) \\ \vdots & \ddots & \vdots \\ 1_{K-1}(n) & \cdots & 1_{K-1}(n+N-1) \end{pmatrix}, \quad (2)$$

where the total number of channels in the primary system is $K \times N$, denoted as C for simplicity. $\mathbf{I}(n)$ is served as the inference for estimation of system load and system parameters. Spectrum sensing distributedly performed at CUs can help CUs make smarter channel access decisions. Let $g(\mathbf{I}(n))$ denotes the load estimation function which maps the channel availability matrix $\mathbf{I}(n)$ to the number of channel occupied in primary system (i.e., system load). The system load l can be intuitively estimated by:

$$l = g(\mathbf{I}(n)) = \sum_{k=0}^{K-1} \sum_{t=0}^{N-1} 1_k(n+t). \quad (3)$$

The mapping between $\mathbf{I}(n)$ and l should be carefully designed by considering characteristics of primary system, such as frame structure, hopping format, or multiplexing method.

B. Parameter Estimation

With the spectrum sensing capability, CUs can perform parameter estimation similar to the centralized controller in traditional CAC. The estimation of system parameters (specifically, arrival rate λ and service rate μ) have been well studied in queueing systems [14]. The maximum likelihood estimation of our model using (1) can be derived as:

$$\hat{\lambda}_n = \frac{\sum_{k=0}^{K-1} \sum_{t=0}^{N-1} \max\left[1_k(n+t) - 1_k(n+t-N), 0\right]}{N}, \quad (4)$$

and

$$\hat{\mu}_n = \frac{-\sum_{k=0}^{K-1} \sum_{t=0}^{N-1} \min\left[1_k(n+t) - 1_k(n+t-N), 0\right]}{N \times l}. \quad (5)$$

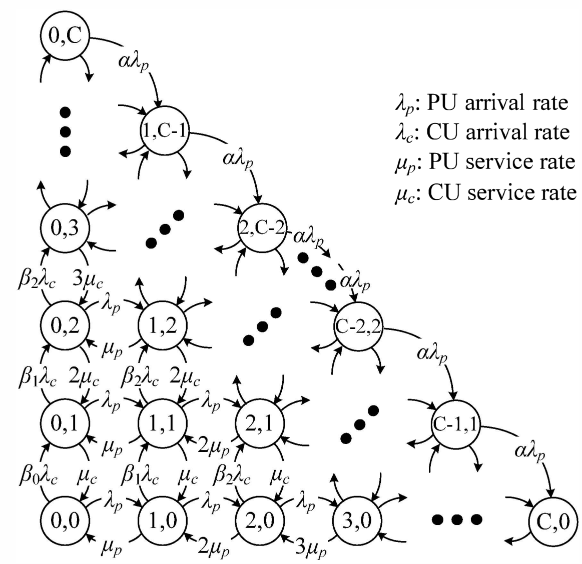

Fig. 1. Transition Diagram

Collections of $\hat{\lambda}_n$ and $\hat{\mu}_n$ give estimations of λ and μ. Suppose that CUs' and PUs' traffic can be distinguished and the observation time is long enough for CUs to perfectly learn the system parameters, then arrival and service rates of CUs' and PUs' requests can be estimated.

C. Channel Access Strategy

We model primary system as a service center with C servers corresponding to the available channels. Suppose that PUs' and CUs' arrivals follow Poisson processes with mean rates λ_p and λ_c, respectively. Suppose that the channel holding times for PU and CU are exponentially distributed with means $\frac{1}{\mu_p}$ and $\frac{1}{\mu_c}$, respectively. Such assumptions are widely adopted in existing literatures [5], [15] for analysis of behavior of channel allocation. With distributive spectrum sensing, we assume that CUs can correctly cognize the load l and above parameters (denoted as system information $\Phi = \{\lambda_p, \lambda_c, \mu_p, \mu_c\}$).

CU makes channel access decision according to the sensed load l and cognized system information Φ. Define CU access policy $\beta_\Phi = \{\beta_{\Phi,l} | l = 0, 1, \ldots, C\}$ as the probabilities that CU accesses the PS-BS upon its arrival when sensing result is Φ and l, where $\beta_{\Phi,l} \in [0, 1]$ and $\beta_{\Phi,l} = 0$ when $l \geq C$. For notation simplicity, we use β_l in the following discussion. To prioritize PUs over CUs, system may drop CU with probability α upon PU arrival when $l = C$. Note that when $\alpha = 1$, this rule is similar to the preemptive rule in the priority queue problem [16].

Let $X(t)$ and $Y(t)$ respectively denote the numbers of PUs and CUs in the system at time t. The system behavior follows the dynamics of a two-dimensional CTMC where the state is $\{X(t), Y(t)\}$ and $\mathbf{\Pi} = \{\pi_{i,j}\}$ is the steady-state probability of state $\{i, j\}$ where $0 \leq i + j \leq C$. The CTMC with corresponding transition rates is shown in Fig. 1. The system starts from state $\{0, 0\}$. If the PU arrived, the state changes from $\{0, 0\}$ to $\{1, 0\}$. At this moment, if the CU arrived, it

$$\begin{cases} 0=-\pi_{i,j}(\lambda_p+\beta_0\lambda_c)+\pi_{i+1,j}\mu_p+\pi_{i,j+1}\mu_c & i=0;j=0\\ 0=-\pi_{i,j}(\lambda_p+\beta_{i+j}\lambda_c+i\mu_p+j\mu_c)+\pi_{i-1,j}\lambda_p+\pi_{i,j-1}\beta_{i+j-1}\lambda_c+\pi_{i+1,j}(i+1)\mu_p+\pi_{i,j+1}(j+1)\mu_c & 0<i+j<C;i,j\neq 0\\ 0=-\pi_{i,j}(\lambda_p+\beta_{i+j}\lambda_c+j\mu_c)+\pi_{i,j-1}\beta_{i+j-1}\lambda_c+\pi_{i+1,j}(i+1)\mu_p+\pi_{i,j+1}(j+1)\mu_c & i=0;0<j<C\\ 0=-\pi_{i,j}(\lambda_p+\beta_{i+j}\lambda_c+i\mu_p)+\pi_{i-1,j}\lambda_p+\pi_{i+1,j}(i+1)\mu_p+\pi_{i,j+1}(j+1)\mu_c & j=0;0<i<C\\ 0=-\pi_{i,j}(\alpha\lambda_p+i\mu_p+j\mu_c)+\pi_{i-1,j}\lambda_p+\pi_{i,j-1}\beta_{C-1}\lambda_c+\pi_{i-1,j+1}\alpha\lambda_p & i+j=C;i,j\neq 0\\ 0=-\pi_{i,j}(\alpha\lambda_p+j\mu_c)+\pi_{i,j-1}\beta_{C-1}\lambda_c & i=0;j=C\\ 0=-\pi_{i,j}(C\mu_p)+\pi_{i,j+1}\alpha\lambda_p+\pi_{i-1,j}\lambda_p & i=C;j=0 \end{cases} \tag{6}$$

access the PS-BS according to β_1. If the CU access the PS-BS, the state changes from $\{1,0\}$ to $\{1,1\}$. When the state is $\{0,C\}$ and the PU arrived, the CU may be dropped according to α. If the CU is dropped, the state changes from $\{0,C\}$ to $\{1,C-1\}$. If the state $\{1,C-1\}$ and the PU departs, the state changes to $\{0,C-1\}$. Similarly, if the CU departs, the state changes from $\{0,C-1\}$ to $\{0,C-2\}$. Other state transition is follow above scheme. The balance equations for CTMC are expressed as (6). The steady-state probability $\mathbf{\Pi}$ for such CTMC can be solved by considering $\mathbf{0}=\mathbf{Q\Pi}$ and $\sum_{i,j}\pi_{i,j}=1$ [14], where $\mathbf{0}$ and $\mathbf{P}$ are $C\times C$ matrices and $\mathbf{Q}$ is a $C\times C\times C\times C$ matrix. The blocking probability b_p for PU is

$$b_p=\sum_{(i+j=C,i\neq C)}(1-\alpha)\pi_{i,j}+\pi_{C,0}, \tag{7}$$

and the dropping probability d_c for CUs' requests is

$$d_c=\sum_{(i+j=C,i\neq C)}\frac{\alpha}{j}\cdot\frac{\alpha\lambda_p}{\alpha\lambda_p+i\mu_p+j\mu_c}\pi_{i,j}. \tag{8}$$

The blocking probability b_c for CUs' requests is

$$b_c=\sum_{i,j}(1-\beta_{i+j})\pi_{i,j}. \tag{9}$$

Note that we can adopt the approximation method [15] to calculate b_p, d_c, and b_c in an efficient way.

Let u_p and u_c respectively denote the utilities of channel access requests of PUs and CUs. Let B_p^*, B_c^*, and D_c^* respectively denote as the QoS constraints in terms of the maximum allowed blocking probabilities for PUs' and CUs' requests, and dropping probability for CUs' requests. Define I_{b_p}, I_{b_c}, and I_{d_c} as the QoS violation indicators. For example, I_{b_p} represents if b_p is greater than B_p^*, that is,

$$I_{b_p}=\begin{cases}1, & \text{if } b_p>B_p^*,\\ 0, & \text{if } b_p\leq B_p^*.\end{cases} \tag{10}$$

If I_{b_p}, I_{b_c}, or I_{d_c} equals to one, there is a corresponding penalty c_{b_p}, c_{b_c} or c_{d_c} proportional to QoS violation. The system utility U for serving PU and CU is defined as

$$\begin{aligned} U &= \sum_{i,j}(iu_p+ju_c)\pi_{i,j}-I_{b_p}(b_p-B_p^*)c_{b_p}\\ &- I_{b_c}(b_c-B_c^*)c_{b_c}-I_{d_c}(d_c-D_c^*)c_{d_c}. \end{aligned} \tag{11}$$

The first term in (11) represents the aggregated utilities collected from serving CUs and PUs. The following terms are the penalty of QoS degradation. However, b_p should not be worse than predefined constraint B_p^* to achieve the fundamental requirement that interference to PU induced by CU is limited. We define a problem **MAXUQ** as follows:

$$\begin{aligned}&\text{Maximize } U\\ &\text{Subject to Constraint } b_p\leq B_p^*\end{aligned} \tag{12}$$

A threshold access (TA) strategy is proposed, where a CU makes a request only if the load l is below a threshold T. That is, $\beta_0=\cdots=\beta_{T-1}=1$ and $\beta_T=\cdots=\beta_{C-1}=0$. Please note that TA strategy is comparable to conventional guard channel policy (GCP) [5] for CAC at PS-BS, where CU and PU requests are analogous to new and handover calls, respectively. With cognitive capability, CUs can actively cognize l and Φ via spectrum sensing to make smarter access decision. We propose an algorithm to dynamically find the optimal TA strategy for **MAXUQ**:

Algorithm 1 COGNITION AND FIND OPTIMAL THRESHOLD

```
1: Cognize the system and estimate Φ
2: Set T = C
3: initialize {β_j = 1 | j = 1, ··· , T − 1} and β_T = 0
4: while true do
5:     Compute b_p
6:     if b_p > B_p^* then
7:         T = T − 1; β_T = 0
8:     else
9:         Exit the while loop
```

Each CU periodically executes Algorithm 1 where spectrum sensing is performed at line 1 to get Φ. Line 3 computes b_p in accordance of CTMC built by Φ. At lines 4-5, CU finds the maximum T for **MAXUQ** where we adopt the property that b_p is a nondecreasing function of T from CTMC. The complexity of Algorithm 1 is $O(C)$.

Upon packet arrival at the CU, the above algorithm is then executed. Based on CU's cognition and the related optimal policy, CCA algorithm compares if current load larger than T to decide if CU accesses the channel or not. Note that the complexity of CCA is $O(1)$.

Algorithm 2 COGNITIVE CHANNEL ACCESS (CCA)

while upon packet arrival **do**
    Execute Algorithm 1 to find optimal threshold and get load l
    if $\beta_l = 1$ **then**
        Make request then access the channel
    else
        Do not make request or access the channel

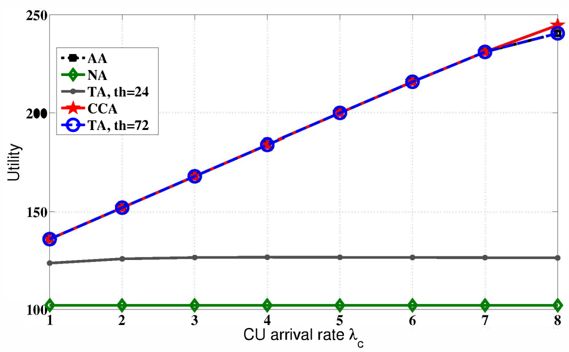

Fig. 2. Utility with respect to CU arrival rate λ_c, where $\lambda_p = 3.0, \alpha = 0.3$

III. NUMERICAL RESULTS

In this section, we investigate the numerical results of proposed algorithms. The figures show the system utilities with respect to the arrival rate of CU with different channel access schemes, e.g., Always Access (AA), Never Access (NA), Threshold Access (TA), and our proposed scheme, Cognitive Channel Access (CCA). The parameters are set that the number of channels $C = 64$, the dropped probability of CU $\alpha = 0.3$, the service rate of PU $\mu_p = 0.15$, the service rate of CU $\mu_c = 0.25$, the Quality of Service (QoS) constraints are $B_p^* = 0.005$, $B_c^* = 0.1$ and $D_c^* = 0.05$, and the penalties if QoS violation occurs are $c_{b_p} = 800$, $c_{b_c} = 20$, and $c_{d_c} = 100$. For the reason that PU should be provided higher QoS, the utility of PU is set higher than that of CU, i.e., $(u_p, u_c) = (6, 4)$.

In the following, we describe the rational of algorithms invetigated in our performance evaluation. AA scheme is that CU always access the channel when arrive. NA means that CU never access the channel, in other words, this scheme is that the system load is always generated by the channel access of PUs. TA is the scheme that CU would access the channel when the system load is less than the threshold T. Here, we provide the high threshold $T = 72$ and low threshold $T = 24$ for the comparison. Finally, CCA is our proposed solution to cognitive access in multichannel wireless networks in order to enhance the system utility.

Fig. 2 shows that NA is the worst scheme because the CUs would never access the channel. For TA with low threshold $T = 24$, although it outperforms NA, it still have a low system utility. The figure also shows that the system utility of the higher threshold is better than the system utility of the lower threshold. The reason is that low threshold would lead to lots of CUs accessing the channel and thus interfere

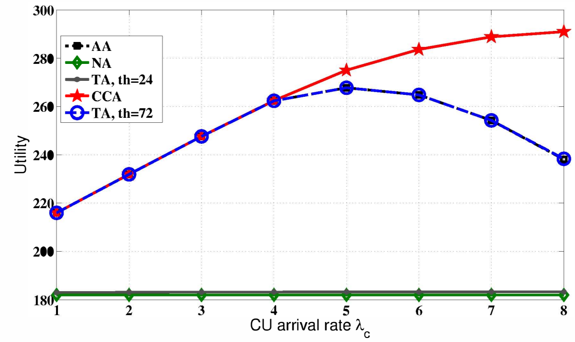

Fig. 3. Utility with respect to CU arrival rate λ_c, where $\lambda_p = 5.0, \alpha = 0.3$

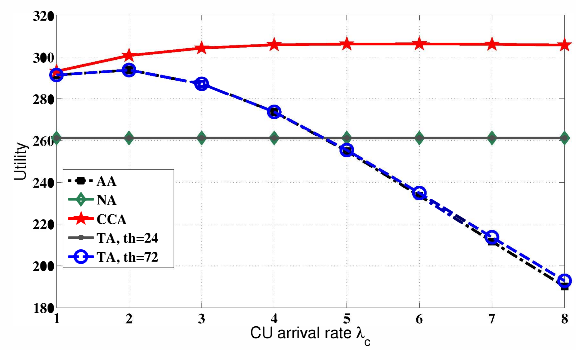

Fig. 4. Utility with respect to CU arrival rate λ_c, where $\lambda_p = 7.0, \alpha = 0.3$

the usage of the channels of the PUs. Furthermore, the red line show that our proposed CCA algorithm outperforms other channel access schemes. It is not a surprising result because the CCA algorithm can always set the best threshold value, i.e., dynamically set the threshold value, thus, the system utility can be maximized.

In Fig. 3, we consider high primary system traffic, i.e., higher λ_p. In this case, the utility of TA with threshold $T = 72$ decreases as the arrival rate of CU λ_c increases. It is due to the reason that the higher arrival rate of PU and CU, the constraint on CU would make the system almost occupied by PUs, which lead to the lower system utility. We also observe that NA and TA with threshold $T = 24$ both remain low utility because the channels are almost allocated by PUs.

When we increase the arrival rate of PU more higher (i.e., $\lambda_p = 7.0$), we can observe in Fig. 4 that the system utility of TA with threshold $T = 72$ decreases quickly when the arrival rate of CU λ_c arises. The reason for this is same to Fig. 3, but the phenomenon in Fig. 4 is more explicit. Again, our proposed CCA algorithm outperforms other channel access schemes because of the dynamic threshold value decision.

Fig. 5 shows that our proposed CCA algorithm explicitly outperforms other schemes. It is due to the reawon that when the traffic of PUs and CUs is higher, we need to decide the threshold more accuracy. Other schemes are the static threshold value decision method, when the threshold is decided, it would never be changed at all. However, our proposed CCA

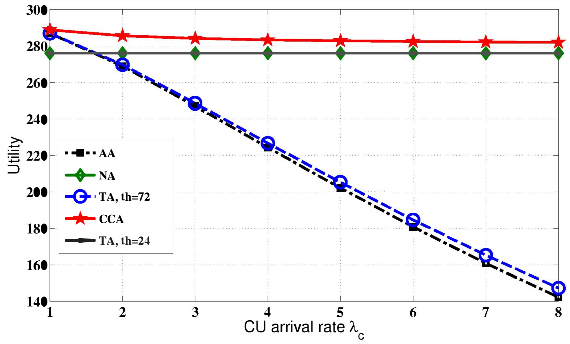

Fig. 5. Utility with respect to CU arrival rate λ_c, where $\lambda_p = 9.0, \alpha = 0.3$

algorithm would always adjust the threshold value according to the sensing ability of CUs. Thus, the CUs always get the idea about the most appropriate threshold value, which lead to the higher system utility than other static schemes. Obviously, we observe from the all figures that whether the arrival rate of PU is high or low, the system utility of our proposed CCA scheme is always outperforms other channel access schemes.

IV. Conclusion

Because of the cognitive functionality of CUs, the channel access can be more intelligent and the channels can be used more efficient. In this paper, we have shown the system modeled by the two-dimension continuous-time Markov chain (CTMC) and we have analyzed the model our proposed. Furthermore, we have proposed two algorithms Threshold Access (TA) and Cognitive Channel Access (CCA), which are the static and dynamic channel access strategy respectively. In section III, we have shown the numerical results by illustrating the four figures and these figures have shown that our proposed CCA algorithm is outperform other channel access schemes. By our proposed CCA algorithm, we can significantly increase the system utility for serving both PUs and CUs in primary system while keeping blocking probability of PUs' requests under a given constraint, which can make the usage of the channels more efficient than traditional channel access schemes.

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