

Enhanced Channel Access Estimation based Adaptive Control of Distributed Cognitive Radio Networks

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Abstract

Spectrum sharing in centrally controlled cognitive radio (CR) networks has been widely studied, however, research on channel access for distributively controlled individual cognitive users has not been fully characterized. This paper conducts an analysis of random channel access of cognitive users controlled in a distributed manner in a CR network. Based on the proposed estimation method, each cognitive user can estimate the current channel condition by using its own Markov-chain model and can compute its own blocking probability, collision probability, and forced termination probability. Using the proposed scheme, CR with distributed control (CR-DC), CR devices can make self-controlled decisions based on the status estimations to adaptively control its system parameters to communicate better.

Keywords: Cognitive radio, Blocking probability, Forced termination probability, Spectrum handoff, Spectrum sharing.

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1. Introduction

In cognitive radio (CR) networks, each cognitive user, or secondary user, has a different channel access probability depending on the network topology to access licensed channels when unoccupied by primary users. Since a user with more neighbors experiences more severe competition in channel access, the events of blocking and collision occur more frequently. In wireless mesh networks, a node with a number of neighbors commonly has a crucial role to support in addition to its own communication needs, such as relaying/forwarding, however, it is rather difficult to be efficient in channel access without accurate channel access estimations.

Due to the importance of CR networks, studies on blocking probability and forced termination probability of cognitive users have been conducted. However most previous studies have analyzed the probability of the entire CR network characteristics. There are few modeling studies based on an individual cognitive user's performance point of view. Disadvantages of modeling of the overall network perspective is that it does not help individual CR nodes to make a decision on when is best to transmit. This paper proposes a channel access modeling scheme of cognitive users considering collisions between cognitive users from an individual cognitive user's point of view with distributed control in CR networks.

The contributions of this paper, compared with related published papers, are explained in the following.

Most papers which cover CR environments use a Markov-chain to analyze centralized CR networks [1]-[4]. Centralized models assume that there is a controller that monitors the entire channel and figures out the conditions of the primary and secondary CR channels.

In addition, the models in [1]-[4] do not consider collision events between cognitive users transmitting at the same time. In the proposed scheme, it is possible to analyze the collision probability of each cognitive user because it considers all possible collision events. As a result, the proposed model is able to accurately derive the individual channel access probability of cognitive users in distributed networks, and can estimate each individual cognitive user's blocking and forced termination probability by observing the CR user's channel conditions.

In [5] and [6], the active probability is used, where active is defined as a function of on-off control in sensor networks. Such approaches cannot characterize the performance when each cognitive user adjusts its own active probability value based on the condition of channel utilization. This is important because in a distributed CR network a CR user can modify its active probability by estimating channel conditions and controlling its transmission to satisfy its own communication needs.

Throughput of cognitive users is analyzed in [7], which is based on control of the arrival rate of all cognitive users. The scheme for adjusting the arrival rate of cognitive users in [7] is dependent on the number of channels unoccupied by primary users or other cognitive users. The method used in [7] is based on adjusting the arrival rate by the number of empty channels, which is inappropriate to adapt to distributed networks because this method is based on the control of the arrival rate in a centralized manner and does not consider the characteristics of a distributed CR network. In addition, since the approach in [7] uses a modeling scheme for the probability of selecting the appropriate channels, it cannot analyze important probabilities in CR networks such as blocking, collision, and forced termination.

The proposed scheme can obtain the steady-state probability of channels looking at each cognitive user using a Markov-chain model, where the steady-state probability, blocking probability, collision probability, access probability, and forced termination probability of each cognitive user can be obtained accurately.

The remaining sections of this paper are organized as follows. In section II, the network model is introduced. Section III presents the performance analysis and section IV concludes the paper.

2. System Model

2.1 Active Probability

The active probability $p(k)$ ($1 \leq k \leq N$) is influenced by the number of cognitive users in the network N , which is a value that adjusts the likelihood of cognitive user k to participate in the competition of channel access by sensing the channel status, which may be idle (unoccupied) or busy (occupied). Since the active probability of each cognitive user can be derived, a cognitive user can access the idle channel more effectively based on the network topology and channels situation (e.g., considering the number of active neighboring users).

2.2 Markov Model for Distributed CR

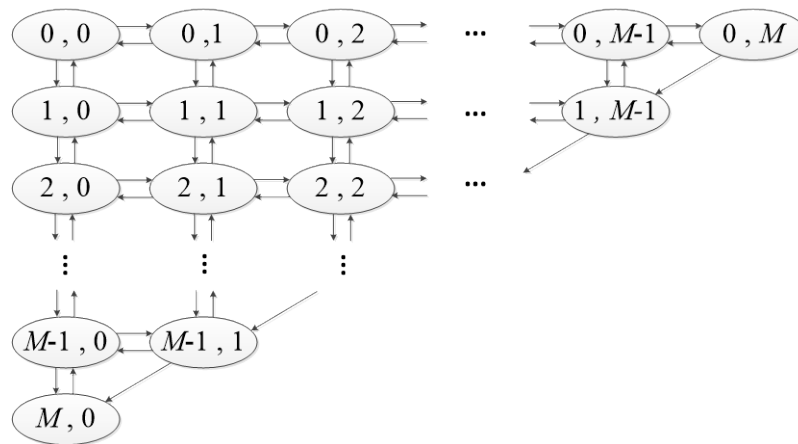


Fig. 1. Markov-chain model for a cognitive user

Fig. 1 presents the Markov-chain model of channel states for a cognitive user’s perspective in the network with M channels where spectrum handoff is possible. The number of all feasible states is $(M+1)(M+2)/2$. In the integer pair (i,j) , i is the total number of primary users in channel use and j is the total number of one-hop neighboring cognitive users using unoccupied channels by primary users. The arrivals of primary users and cognitive users are assumed Poisson processes with arrival rates λ_p and λ_c , respectively. The service times are exponentially distributed with rates μ_p and μ_c , respectively [1].

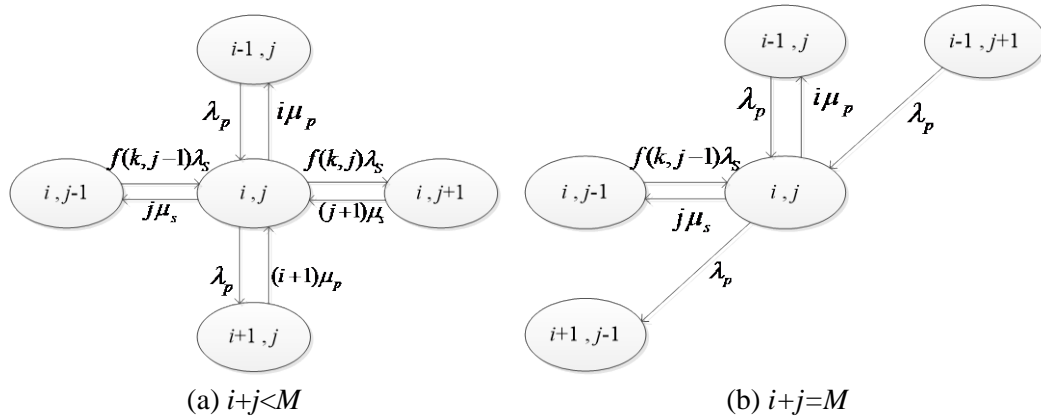


Fig. 2. Markov-chain model for a cognitive user

The state transition diagram with spectrum handoff of cognitive user k is depicted in **Fig. 2**. In state transition, $f(k, j)$ is a function of probability that one of the one-hop neighboring cognitive users of cognitive user k accesses an unoccupied channel when j neighboring cognitive users are already using the channels. This probability function can be expressed as follows

$$f(k, j) = \binom{\rho(k) - j}{1} \tilde{p}(k) (1 - \tilde{p}(k))^{\rho(k) - j} \tag{1}$$

where $\rho(k)$ is the total number of one-hop neighboring cognitive users of k , and $\tilde{p}(k)$ is the average of active probabilities of one-hop neighboring cognitive users of k .

For $(i, j) \in \Phi_k$, $\phi_k(i, j)$ is the indicator function of cognitive user k in **Fig. 2**, where Φ_k is the set of feasible states. The indicator function of user k can be represented as follows.

$$\phi_k(i, j) = \begin{cases} 1 & \text{if } (i, j) \in \Phi_k \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The balance equation of **Fig. 2 (a)** can be represented as (3) where $\pi_k(i, j)$ is the state probability of state (i, j) of cognitive user k .

$$\begin{aligned} & \{i\mu_p + f(k, j)\lambda_s + \lambda_p + j\mu_s\} \pi_k(i, j) \phi_k(i, j) \\ &= \lambda_p \pi_k(i-1, j) \phi_k(i-1, j) + (j+1)\mu_s \pi_k(i, j+1) \phi_k(i, j+1) \\ & \quad + (i+1)\mu_p \pi_k(i+1, j) \phi_k(i+1, j) + f(k, j-1)\lambda_s \pi_k(i, j-1) \phi_k(i, j-1) \end{aligned} \tag{3}$$

Similarly, the balance equation of **Fig. 2 (b)** can be expressed as follows.

$$\begin{aligned}
 & \{i\mu_p + \lambda_p + j\mu_s\} \pi_k(i, j) \phi_k(i, j) \\
 &= \lambda_p \pi_k(i-1, j) \phi_k(i-1, j) + \lambda_p \pi_k(i-1, j+1) \phi_k(i-1, j+1) \\
 & \quad + f(k, j-1) \lambda_s \pi_k(i, j-1) \phi_k(i, j-1)
 \end{aligned} \tag{4}$$

Considering the effect of spectrum handoff, the number of all feasible states is $(M+1)(M+2)/2$, and the sum of all feasible states is 1, as presented in (5). By solving the balance equations, all state probabilities of a cognitive user can be found.

$$\sum_{i=0}^M \sum_{j=0}^M \pi_k(i, j) \phi_k(i, j) = 1 \tag{5}$$

2.3 Blocking Probability, Collision Probability and Access Probability

In CR networks, the *blocking* of cognitive users occurs when the state of a cognitive user becomes active and a cognitive user starts sensing the channels, but the channels are occupied by primary users or its one-hop neighboring cognitive users. The blocking probability of cognitive user k ($P_B(k)$), can be obtained by multiplying the active probability of k ($p(k)$) and applying the summation of all full occupied states ($\hat{P}_B(k)$). Therefore the blocking probability of cognitive user k can be calculated from the Markov-chain model as follows.

$$P_B(k) = \sum_{i+j=M} \pi_k(i, j) p(k) = \hat{P}_B(k) p(k) \tag{6}$$

If the active probability of cognitive user k is 1, $P_B(k)$ equals $\hat{P}_B(k)$.

For collision-free channel access for cognitive user k , at least one or more channels need to be idle, and the channels of user k 's one-hop neighboring cognitive users must not be fully used. Fig. 3 illustrates this 'hidden terminal problem' case.

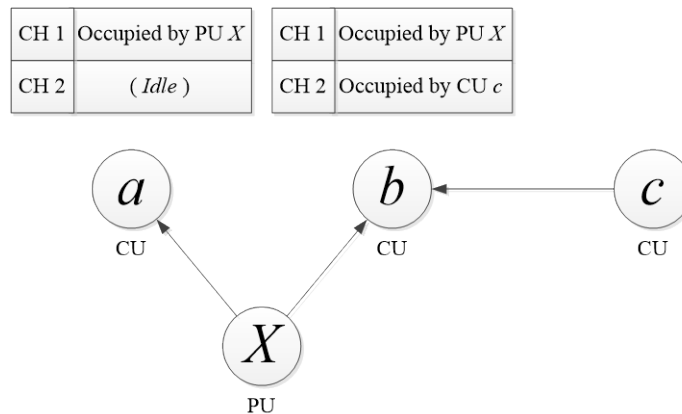


Fig. 3. Hidden terminal problem

In Fig. 3, when a cognitive user a senses the state of two channels, it draws inference that only CH 1 is occupied by primary user (PU) X , and CH 2 is not used by any other users. However, from the cognitive user (CU) b 's perspective, it detects that CH 1 is used by PU X , but CU b can sense that CH 2 is used by its one-hop neighboring CU c . In this situation, if CU a broadcasts using CH 2, a collision occurs at CU b . Therefore, collision of a cognitive user trying to access a channel occurs when the channels are fully used by at least one of the one-hop neighboring users.

For successful channel access of a cognitive user, the blocking and collision should not occur at the same time when a cognitive user is active. The representation of successful channel access probability of a cognitive user is presented in (8). $P_{Nonblock}(k)$ in (7) is the non-blocking probability of all one-hop neighboring users of cognitive user k , when the number of one-hop neighboring users of k is n (l_1, l_2, \dots, l_n).

$$\begin{aligned} P_{Nonblock}(k) &= \left(1 - \sum_{i+j=M} \pi_{l_1}(i, j)\right) \left(1 - \sum_{i+j=M} \pi_{l_2}(i, j)\right) \cdots \left(1 - \sum_{i+j=M} \pi_{l_n}(i, j)\right) \\ &= (1 - \hat{P}_B(l_1))(1 - \hat{P}_B(l_2)) \cdots (1 - \hat{P}_B(l_n)) \end{aligned} \quad (7)$$

$$\begin{aligned} &= \prod_{l \in \Psi(k)} (1 - \hat{P}_B(l)) \\ P_A(k) &= (1 - \hat{P}_B(k)) P_{Nonblock}(k) p(k) \end{aligned} \quad (8)$$

In (7), $\Psi(k)$ is the set of all one-hop neighboring users of cognitive user k .

The collision probability of cognitive user k can be obtained as (9) assuming that the channel environment of primary users' usage is equal to all cognitive users in the network.

$$P_C(k) = (1 - \hat{P}_B(k))(1 - P_{Nonblock}(k))p(k) \quad (9)$$

The idle (i.e., the non-active) probability of cognitive user k can be expressed as (10) based on the fact that the probability sum of all possible outcomes is equal to 1.

$$\begin{aligned} P_I(k) &= 1 - p(k) \\ &= 1 - p(k) \left[\hat{P}_B(k) + (1 - \hat{P}_B(k)) \right] \\ &= 1 - p(k) \left[\hat{P}_B(k) + (1 - \hat{P}_B(k)) \{ P_{Nonblock}(k) + (1 - P_{Nonblock}(k)) \} \right] \\ &= 1 - p(k) \hat{P}_B(k) - p(k) (1 - \hat{P}_B(k)) P_{Nonblock}(k) - p(k) (1 - \hat{P}_B(k)) (1 - P_{Nonblock}(k)) \\ &= 1 - P_B(k) - P_A(k) - P_C(k) \end{aligned} \quad (10)$$

2.4 Forced Termination Probability and Throughput

Another important issue to analyze in distributed CR networks is forced termination. A cognitive user should vacate using a channel if a licensed primary user arrives. If there is another channel, a cognitive user can perform spectrum handoff. However, if not, forced termination occurs. In other words, the forced termination probability is the probability that a cognitive user already accessing and using a channel is forced to disconnect the service

because of the primary user's appearance and has no other available channel to conduct handoff to. The forced termination probability can be obtained from the Markov-chain model of one-hop neighboring cognitive users. In the Markov-chain model of cognitive user k , the forced termination probability can be derived by subtracting the probability that forced termination will not occur from the access probability of cognitive user k , which results in the form of

$$P_F(k) = \frac{\lambda_p P_A(k) - P_{Fnot}(k)}{\lambda_s P_A(k)} \quad (11)$$

where $P_{Fnot}(k)$ is the probability that successfully channel access of cognitive user k will not result in forced termination because there is another vacant channel to perform spectrum handoff, which is represented in (12).

$$P_{Fnot}(k) = \prod_{l \in \Psi(k)} (1 - P_B(l)) - \prod_{l \in \Psi(k)} \left\{ (1 - P_B(l)) - \sum_{i+j=M-1} \frac{1}{j+1} \pi_l(i, j) \right\} \quad (12)$$

Assuming that all cognitive users have an identical transmission rate, normalized to 1 bit per unit time, each cognitive user's throughput can be expressed as (13).

$$S(k) = \frac{P_A(k)}{p(k)} (1 - P_F(k)) \lambda_s \left(\frac{\mu_s}{1 - P_F(k)} \right)^{-1} \quad (13)$$

3. Simulation & Analysis

In this section, by comparing the developed analytical results to the simulation results, the accuracy of the proposed modeling scheme, CR with distributed control (CR-DC), is demonstrated. The example networks of [8] are used as CR networks as illustrated in Fig. 4. In Fig. 4 (a), for example, the nodes 5 and 10 who have relatively a large number of one-hop neighboring users have a larger value of blocking and collision probability. As a result, they have less channel access probability. On the contrary to this, cognitive users such as 1, 7, and 8 who have a relatively small number of neighboring users have a bigger chance to access the channel. The reason for using Fig. 4 is that these topologies are suitable to apply to distributed CR networks because they are representatives of (a) simple and (b) complex wireless mesh networks. In addition, because the nodes in the network topology have a different number of one-hop neighboring nodes, they are used to analyze the accuracy of the proposed modeling scheme in this paper. Each node is assumed to be a cognitive user in the example networks and M is set to 2.

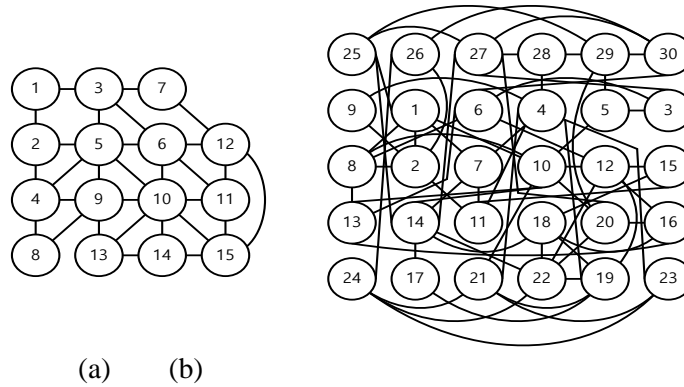


Fig. 4. Example networks presented in [8]

The access probability, blocking probability and collision probability based on the arrival rate of the primary users are analyzed for 15-node networks in Fig. 5. It is shown that the proposed CR-DC scheme provides an accurate performance compared to actual cognitive users in distributed cognitive networks.

The performance comparison with the centralized modeling algorithm from a position of channels centralized [2] is presented in Fig. 6. For accurate comparison with CR-DC, the number of sub-channels (N in [2]) is 1 and the number of channels (M in [2]) is 2. The performance of average throughput of each cognitive user in [2] does not consider the collisions between cognitive users. In addition, throughput analysis in [2] does not consider the topology of the network, therefore, throughput is only dependent on the number of channels regardless of the number of nodes in the network. Consequently there is a difference between the throughput analysis of [2] and simulation results in distributed CR networks. On the other hand, the proposed CR-DC considers the collisions between cognitive users and can precisely analyze the throughput of each cognitive user in a distributed CR network by taking into account the topology of the network.

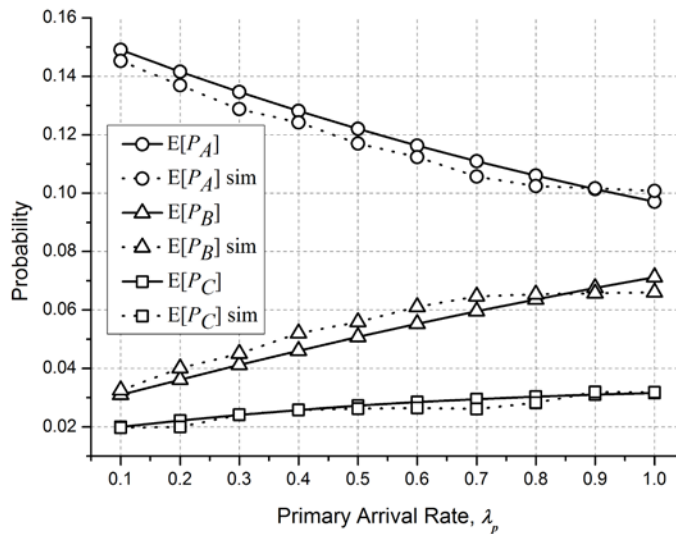


Fig. 5. Access probability, blocking probability and collision probability

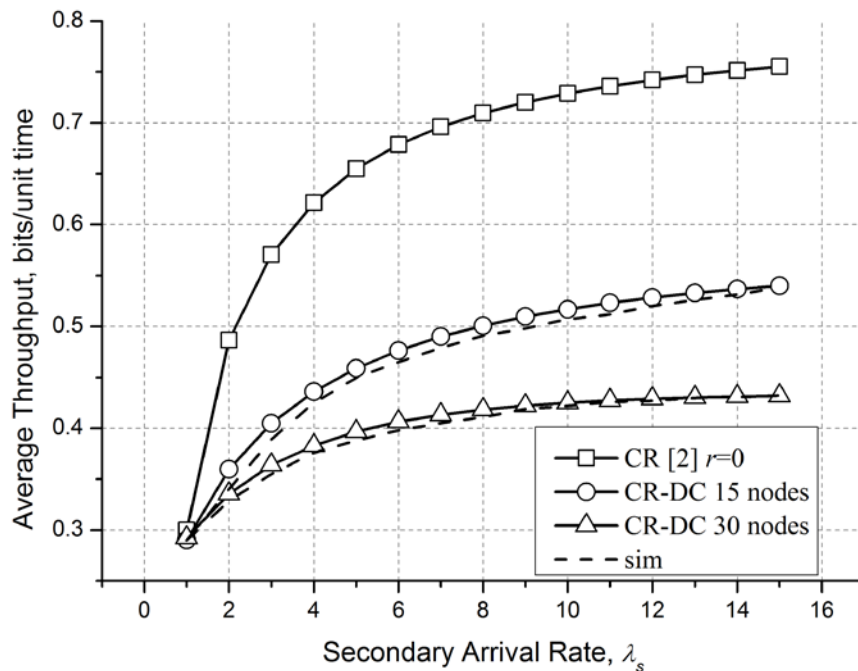


Fig. 6. Throughput comparison between the centralized modeling and CR-DC

4. Conclusion

The proposed CR-DC scheme can be used to obtain the steady-state probability of channels looking at each cognitive user by using a Markov-chain model. Through the steady-state probability, the blocking probability, collision probability, access probability, and forced termination probability of each cognitive user can be obtained accurately for a distributed CR network. Using the computed access probability of each cognitive user in the random channel access environment, the performance can be accurately obtained and using this information the cognitive users in the network can make self-controlled decisions (based on the status estimations) to adaptively control their system parameters to communicate better.

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