Analysis of Distributed Dynamic Spectrum Access Scheme in Cognitive Radios

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Abstract—The problem of distributed Dynamic Spectrum Access (DSA) using Continuous Time Markov Model (CTMC) in Cognitive Radio (CR) is considered in this paper. DSA is an approach which facilitates the opportunistic use of licensed spectrum for the unlicensed (secondary) users without causing harmful interference to the licensed (primary) users. In the proposed distributed DSA scheme, each secondary user perceives the spectrum dynamics as a CTMC and access the spectrum. This scheme is a heuristics based approach which makes use of the estimated spectrum idle-probability and the interference each user experiences, to iteratively update user statistics. Here the main objective of this scheme is to attain a best set of access probabilities based on instantaneous interference rather than attaining a single set of optimum access probabilities. Simulation results show the effectiveness of the proposed algorithm in terms of throughput and establish the access probability variations of the secondary users.

Keywords—Cognitive Radio, CTMC, distributed scheme Dynamic Spectrum Access.

I. INTRODUCTION

Radio spectrum is a limited source and is completely regulated by authorized bodies like Federal Communication Commission (FCC) [1]. CR Technology is proposed as a novel solution [1] for the conflicts between the spectrum scarcity in unlicensed band and low spectrum utilization in licensed band. This technology could be made use of in the future to make opportunistic use of the licensed spectra by unlicensed users. Unlicensed users equipped with CRs may in future be able to sense and opportunistically utilize a licensed spectrum when the corresponding licensed user is not making use of it. This is known as opportunistic spectrum access /DSA. In the existing DSA/CR terminology, licensed users are called the primary users and unlicensed users are called the secondary users [2]. Secondary users are allowed to share the licensed spectrum only when the primary users are unoccupied. This spectrum occupancy awareness can be achieved by spectrum sensing algorithms such as energy detection, matched filtering and feature detection [3]. Upon identifying the free spectrum, the secondary users can use it for their own communication without causing interference to the primary users.

The application of CR technology to dynamic spectrum access has led to interest in developing spectrum access algorithms and policies for making efficient use of idle spectrum. In this context, there are many existing contributions which model the primary user – secondary user interactions using Markov models for dynamic spectrum sharing [4-9]. In [4] – [5], the authors proposed a centralized scheme for dynamic spectrum access using CTMC model of primary user – secondary user interactions. The authors of [6] proposed spectrum access schemes using CTMC with optimal channel reservation for secondary users. In [7] the authors evaluated the performance of opportunistic spectrum access using a two dimensional Markov model for a military environment. In [8], a framework based on Discrete Time Markov Chain for spectrum channelization between primary-secondary spectrum sharing was proposed. Their work also includes errors resulting from spectrum sensing for the performance evaluation and extended in [9] for flexible spectrum channelization schemes.

CR networks of the future may consist of PU and SUs belonging to multiple networks operated by different service providers. This led to the distributed access coordination solutions as opposed to centralized ones. To this end, there are several distributed schemes proposed in the literature. In [10], the authors proposed a distributed algorithm for learning and cognitive medium access using a Multi Armed Bandit model was proposed based on the assumption of an i.i.d distribution of primary user transmissions. In [11], a game theoretic framework and no regret learning algorithm was proposed for distributed adaptive channel allocation. Another distributed approach to optimize the efficiency of spectrum allocation using a local bargaining mechanism was proposed in [12].

Thus in the literature, several centralized and distributed DSA schemes [13] showing successful enhanced performance to increase the spectrum efficiency were found. A first step towards a fully distributed DSA using Markovian model was proposed in [14] both for perfect sensing and imperfect sensing. In this paper, the access probability variations and the estimated statistics for the distributed DSA scheme [13-14] are analyzed.

Further this paper is organized as below: in Section II the System Overview is discussed; in Section III, the CTMC model and the distributed DSA scheme is discussed; Simulation results and analysis are discussed in Section IV and Section V is the conclusion part of the paper.
II. SYSTEM MODEL

A rudimentary CR system which employs the proposed scheme is shown in Fig 1. The main objective of the proposed scheme is to optimize the throughput for multiple secondary users operating in the licensed spectrum of a single primary user. To do this, best set of access probabilities must be calculated. Access probabilities are the probabilities with which the secondary users access the spectrum when it is being used by other secondary users. In other words, access probabilities provide control over the amount of interference experienced by secondary users on an average. The challenge is to optimize the access probabilities such that interference is not high enough to cause severe loss of throughput, while at the same time not being low enough to result in loss of transmission opportunities.

Fig. 1 CR System Model [14]

The access probability of each secondary user is time varying and is given by the spectrum idle probability estimate from the perspective of that secondary user. It is controlled by a part of the spectrum access algorithm called the update rule. The update rule in turn makes use of the information provided by the interference measurement unit to update the access probability. At any point of time, it is the instantaneous interference experienced by a secondary user that determines the access probability. Thus the proposed scheme is therefore not a scheme that results in convergence to a single set of optimum access probabilities, but is rather an adaptive scheme which approximates the best of access probabilities based on instantaneous interference information. This will be apparent in the simulation results shown in section V.

III. CTMC MODEL AND DISTRIBUTED DSA FOR SPECTRUM ACCESS

In this section, the CTMC model for dynamic spectrum access involving one primary user and multiple secondary users is described. A system with single primary user (P) and two secondary users (A and B) is taken for illustration as in [4]. The primary-secondary spectrum sharing is modeled as CTMC based on the assumptions of Poisson arrival of service requests (λ) and exponentially distributed service rates (μ). The arrival rates of the users P, A and B are denoted by λP, λA and λB respectively. Similarly the service rates for P, A and B are μP, μA and μB.

Fig.2. shows the CTMC state transition diagram for DSA with one primary user P and two secondary users A and B. This can also be extended to one primary and N number of secondary users as discussed in [5]. State S0 is defined as the idle state of the spectrum. When secondary user A (or B) wants to start its communication, it first senses the spectrum. If the spectrum is found idle, the state transits from S0 to S_A (or S_B) at a rate of λ_A (or λ_B). If user A (or B) completes its service before any request from user B (or A), the CTMC transits to state S0 with a rate of μ_A (or μ_B). Otherwise the state transition will be to state S_AB with a rate of λ_B (or λ_A) where both secondary users share the spectrum. However, when the primary user appears, the CTMC transits to state S_P with an arrival rate of λ_P. α_A1, α_A2, α_B1, α_B2 are the access probabilities of the secondary users. The secondary users access with probabilities α_A1 = α_A2 = 1, when the spectrum is in idle state. When other secondary user is utilizing the spectrum, the secondary user estimates the access probabilities so as to minimize the interference.

Fig. 2 CTMC State diagram with access probabilities [4]

Based on the above model, we can derive mathematical expressions relating the state probabilities [4], S0, S_P, S_A, S_B and S_AB and as given below.

\[ \mu_A P_A + \mu_B P_B + \mu_P = (\alpha_A \lambda_A + \alpha_B \lambda_B + \lambda_P) P_0 \]  
\[ \alpha_A \lambda_A P_0 + \mu_B P_2 = (\mu_A + \alpha_A \lambda_B + \lambda_P) P_A \]  
\[ \lambda_P (P_0 + P_A + P_B + P_{AB}) = \mu_P P_P \]  
\[ \alpha_B \lambda_B P_0 + \mu_A P_2 = (\mu_B + \lambda_P + \alpha_A \lambda_A) P_B \]  
\[ \alpha_A \lambda_A P_A + \alpha_B \lambda_B P_B = (\mu_B + \lambda_P + \alpha_A \lambda_A) P_{AB} \]  
\[ P_0 + P_A + P_B + P_{AB} + P_2 = 1 \]

To obtain the state probabilities \( P = [P_0, P_A, P_B, P_{AB}, P_P] \), we solve the equations, \( QP = 0 \) and \( \sum P = 1 \) where Q is the infinitesimal generator matrix given by eqn (8) and can be constructed from eqn (1) - (5),
average throughput per secondary user is reduced. If the number of secondary user constructing the infinitesimal generator matrix for N users and accordingly calculates the spectrum access probability. Thus, each secondary user in environment and accordingly they should increase their spectrum access opportunities. Thus, each secondary user should learn the statistics from the perspective of that user.

In such a distributed scheme, each secondary user increases, the contention for spectrum also increases and the average throughput per secondary user is reduced.

In this model, the secondary network is distributed and does not have a centralized authority for their spectrum access coordination. In such a distributed scheme, each secondary user should learn the statistics from the environment and accordingly they should increase their spectrum access opportunities. Thus, each secondary user in the network perceives the spectrum dynamics as a CTMC and accordingly calculates the spectrum access probability.

The main objective of the proposed distributed scheme is to calculate the access probability for secondary user from the perspective of this user. The CTMC model makes it easy using the infinitesimal generator matrix to calculate the probabilities of spectrum utilization by primary and other secondary users if the arrival and departure rates are known. More significantly, it is possible to directly calculate the probability \( P_0 \), the spectrum idle probability using only the arrival and departure rates. We use this as a rule to update the estimates – initialised on the assumption that the other secondary users access the spectrum with a probability \( P_0_i_ \) from the previous iteration.

Heuristic 1: Interference for more than a certain fraction of time during a given transmission slot indicates an overestimated spectrum idle probability \( (P_0) \) i.e., underestimated arrival rates and overestimated service rates. For example, if a user does not experience interference for a prolonged period of time, it would be an advantageous strategy to increase its access probability until it experiences a minimum amount of interference. This can be achieved by increasing the service rate and reducing the arrival rate. We use this as a rule to update the estimates – initialised on the basis of the above assumption over time.

Unlike a centralised scheme, the decision of one secondary user to interfere with another has to be made by the secondary user itself.

Finally, we define the time-evolving access probability and the interference ratio which is used for updating the user’s statistics in a distributive manner as given below:

**Definition 1:** The time-evolving access probability of each secondary user is the \( P_0 \) estimate, \((P_0_i_) \) which is calculated from the perspective of that user.

**Definition 2:** Interference Ratio (IR) is the ratio of cumulative time period for which interference occurs during a transmission slot \( (T_i) \) to the total duration of a transmission slot \( (T) \).

\[
IR = \frac{T_i}{T} \tag{12}
\]

The proposed scheme designed on the basis of the above definitions and the previously formulated assumptions and heuristics are summarised in Table I and Table II [14].

The constants \( b_{ij} \) and \( b_{ji} \) represent the control parameters

**TABLE I**

<table>
<thead>
<tr>
<th>PROPOSED ALGORITHM FOR DSA SCHEME</th>
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<td>Distributed DSA Algorithm</td>
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- **For each secondary user** \( i \),
  1. Initialize: \( \lambda_i, \mu_i \) for all \( i \neq i \)
  2. Calculate \( P_0 \) using \( (\lambda_p, \mu_p) \) and all \( (\lambda_j, \mu_j), j \neq i \)
  If there is a need to transmit,
  3. Sense the spectrum. If the primary user is not transmitting, then access the spectrum with a probability \( P_0 \). Else keep sensing.
  4. Sense the spectrum. If secondary user \( j (j \neq i) \) is transmitting, then access the spectrum with a probability \( P_0 \).
  Update all \( (\lambda_j, \mu_j), j \neq i \) based on the interference encountered during transmission (Refer update rule in Table II).

**TABLE II**

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<th>UPDATE RULE FOR DSA</th>
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| For each secondary user \( i \),
  1. Calculate the Interference Ratio (IR).
  2. If \( IR > IR_{ref} \) Then go to Step 3 Else go to Step 4.
  3. \( \lambda_i = \lambda_i - b_{ij} ; \mu_i = \mu_i + b_{ij} \) for all \( j \neq i \).
  Go to Step 5.
  4. \( \lambda_j = \lambda_j - b_{ij} ; \mu_j = \mu_j - b_{ij} \) for all \( j \neq i \).
  5. Recalculate \( P_0 \) using the estimates calculated in Steps 3 and 4 on the assumption that the other secondary users access the spectrum with a probability \( P_0 \) from the previous iteration.
  Use \( P_0 \) as the new access probability.
of the algorithm, the magnitudes and signs of which have to be chosen on the basis of the condition we place on IR in the form of the reference value IR_{ref}.

IV. SIMULATION RESULTS

For simulation purposes, the maximum achievable throughput of the secondary users is set to 4.45 Mbps. Spectrum occupancy measurements [15] show that licensed users typically utilise the spectrum about 45% of the time. Hence the arrival rate, service rate pair [14] of the primary user (λ_p, μ_p) is set to (85, 100) s^{-1}. The arrival rate of secondary user B is assumed to be λ_B = 85 s^{-1} and the arrival rate of secondary user A ̂λ_A is varied from 70 to 100 s^{-1} for analysis. The departure rates of both the secondary users are set to 100 s^{-1}.

A. Secondary User Throughput Analysis

The throughput analysis for the primary user and the secondary users for the proposed scheme is shown in Fig.3. It is evident that when ̂λ_A < 85 s^{-1}, the throughput of the secondary user A is less than the throughput of the secondary user B. When ̂λ_A > 85 s^{-1}, the throughput of secondary user B decreases. This is because the estimated access probability is more for user B till ̂λ_A = 85 s^{-1}, and decreases when the arrival rate of user A increases beyond 85 s^{-1}.

B. Access Probability

Fig.4 and Fig.5 shows the access probability estimates of User A and User B for varying arrival rates of User A and Primary User respectively. The access probability estimate of User A decreases as its arrival rate increases and the access probability estimate of User B is almost constant as the arrival rate of User B is constant. When the arrival rate of primary user is varied, the access probabilities of both the secondary users are reduced. Here, the access probability of User A is more than User B as the actual arrival rate of User A is fixed at 70 s^{-1} and that of User B is fixed at 85 s^{-1}.

C. Estimated Arrival Rates

The arrival rate estimate of User A and User B for varying actual arrival rates of User A is shown in Fig.6. The arrival rate estimate of User A is actually the estimated value by User B in order to determine its access probability based on the interference encountered when both users access the spectrum at the same time. Similarly the arrival rate estimate of User B is actually the value estimated by User A to determine its own access probability. It can be seen estimated values closely match with the actual values.

V. CONCLUSION

This paper describes the access probability variations and estimated statistics for the distributed DSA scheme based on CTMC model for the spectrum access of secondary users, so as to maximize the throughput of the secondary users. Secondary users perceive the behavior of the spectrum occupancy as a CTMC model. They learn the statistics from the environment based on the interference countered during transmission and calculate their own access probabilities. Simulation results show the throughput attained by the secondary users and the variations in access probabilities and estimates statistics for the distributed DSA scheme.
REFERENCES


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