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Research Article

Distributed Cognitive Radio Spectrum Access with Imperfect Sensing Using CTMC

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Cognitive radio (CR) has become an efficient approach for the utilization of scarce spectrum by enabling spectrum access in an opportunistic manner. With increasing wireless network service providers, users, and applications, it is indispensable to optimize usage of even parts of the spectrum that are licensed. Dynamic spectrum access (DSA) is an approach which facilitates the opportunistic use of licensed spectra, when they are idle. In this paper, a primary prioritized distributed DSA algorithm using continuous-time Markov chain (CTMC) model is proposed. In a distributed scheme, each secondary user needs to be aware of the statistics—arrival and service rates—of the other secondary users to optimize the throughput while maintaining fairness. A heuristics-based approach is formulated making use of the estimated spectrum idle probability and the interference each user experiences to iteratively update user statistics. This framework is also extended to incorporate the effects of imperfect spectrum sensing in the form of misdetection and false alarms. Simulation results show that the proposed algorithm attains an overall throughput that is better than CSMA when the primary user spectrum utilization is around 45%. The degradation in throughput caused by imperfect sensing over perfect sensing is also analyzed.

1. Introduction

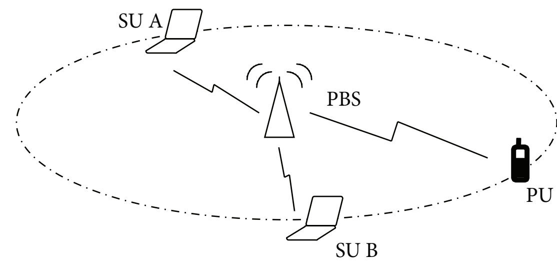
Radio spectrum is a limited source and is completely regulated by authorized bodies such as the Federal Communication Commission (FCC) [1]. CR technology is proposed as an innovative solution for the conflicts between spectrum scarcity in unlicensed bands and low spectrum utilization in licensed bands. In the existing CR terminology, licensed users are called the primary users and unlicensed users are called the secondary users [2]. Secondary users equipped with cognitive capabilities are allowed to share the licensed spectrum only when it is unoccupied. This spectrum occupancy awareness can be achieved by a variety of spectrum sensing algorithms among which the energy detection, matched filtering, and feature detection are popular [3]. Upon identifying the free spectrum, the secondary users can use it for their own communication without causing interference to the primary users. This form of CR dynamic spectrum sharing in which the primary user's spectrum is open to secondary users is called spectrum overlay approach or hierarchical spectrum access [4]. Another approach for CR dynamic spectrum sharing is spectrum underlay in which the primary and secondary users coexist together. In this technique, the secondary users are allowed to use the primary spectrum if it operates below the noise floor level of primary users. Alternatively, CR spectrum sharing techniques can be implemented either cooperatively or in the form of coexistence. In the cooperative scenario, primary user can communicate the spectrum availability to the secondary users and thereby demand payment for the usage [5]. Coexistence approach is essentially the spectrum overlay case where the secondary users identify spectrum holes, occupy it, and hand it over to the primary user when it appears again.

In this context, there are many existing contributions which model the primary user-secondary user interactions for spectrum sharing using Markov models [6–11]. In [6, 7], a CTMC framework is proposed for modeling the interactions between the primary user and the secondary users. The authors evaluated the optimum access probabilities for the secondary users to maximize their throughput and maintain fairness. But their contribution mainly focused on a centralized approach and they do not consider the effects of imperfect spectrum sensing. Alternatively, we propose a distributed approach for DSA and consider the sensing errors for performance evaluation. The authors of [8] proposed spectrum access schemes using Markov chain with optimal channel reservation for secondary users which is particularly a channelization scheme. In [9], the performance of opportunistic spectrum access has been evaluated using a two-dimensional Markov model for a military environment. In [10], a framework based on discrete-time Markov chain is proposed for primary-secondary spectrum sharing. This framework is also a spectrum channelization scheme and included the errors resulting from spectrum sensing for performance evaluation. This model is extended in [11] for flexible spectrum channelization schemes.

Apart from Markovian models, several distributed schemes have been proposed in the literature. In [12], the authors proposed distributed algorithms for learning and cognitive medium access using a multiarmed bandit model. In [13], a game theoretic framework is proposed for distributive adaptive channel allocation. Another distributive approach to optimize the efficiency of spectrum allocation using a local bargaining mechanism is proposed in [14]. Alternatively, we propose a distributed algorithm for DSA using CTMC model.

Thus, in the literature, several dynamic spectrum access schemes showing successful enhanced performance in increasing the spectrum efficiency are found. As CR networks of the future may consist of primary and secondary users belonging to multiple networks operated by different service providers, we look for distributed solutions as opposed to centralized ones. Literature review reveals that there is no distributed scheme based on Markovian model for primary user-secondary user interactions. Hence, in this paper, a CTMC-based distributed DSA scheme is proposed and the performance of primary and secondary user spectrum utilization in terms of throughput and fairness under both perfect and imperfect spectrum sensing is analyzed. An algorithm for distributed DSA named as distributed primary prioritized DSA Markovian access (DPMA) algorithm has been developed. This is an updated version of the algorithm proposed in [15]. The performance of the proposed algorithm is evaluated and compared with the conventional CSMA scheme. False alarms and misdetections resulting from imperfect sensing are also considered for performance evaluation.

Further, this paper is organized as below: in Section 2, the system model is discussed; in Section 3, the distributed primary prioritized CTMC model is described and the DPMA algorithm is explained in Section 4; Simulation results and analysis are discussed in Section 5 and Section 6 is the conclusion part of the paper.



PU: primary user

PBS: primary base station

SU A: secondary user A

SU B: secondary user B

Figure 1: System model for DSA [6].

2. System Model

A DSA system involving one primary user and multiple secondary users opportunistically sharing the licensed spectrum is considered. A DSA system with single primary user (P) and two secondary users (A and B) is taken for illustration as in [6] and shown in Figure 1. 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 λ_{P}, λ_{A}, and λ_{B}, respectively. The service rates for P, A, and B are denoted by μ_{P}, μ_{A}, and μ_{B}, respectively.

In our model, the secondary users are allowed to access the primary spectrum when it is found idle. As this scheme is primary prioritized, whenever the primary user reappears, the secondary users should vacate the spectrum and leave it to primary. The secondary network is distributed and does not have a centralized authority for their spectrum access coordination. In a distributed scheme, each secondary user should learn the statistics from the environment and accordingly they should increase their spectrum access opportunities.

An example illustration for throughput with respect to time [6] for two secondary users and one primary user is shown in Figure 2. This example illustrates that at time t_1, secondary user A accesses the spectrum and finishes its service at time t_2. At time t_3 secondary user B occupies the spectrum. When the primary user appears at time t_4, secondary user B vacates the spectrum and leaves it to primary. At time t_5, when primary user finishes its service, secondary user B resumes its service again. At the same time, secondary user A shares the spectrum with B. But this may result in throughput degradation because of interference between them. At time t_7, user B finishes its service and after sometime, say at t_8 user A occupies the band as it is free. At time t_9, as the primary user recommences, user A vacates the band and leaves it to primary. When primary user vacates the spectrum at t_{10}, user A again resumes its service.

The maximum data rate for any secondary user i which operates independently in the spectrum band is given by [7, equation (1)],

$$R_1^i = W \log_2\left(1 + \frac{p_i G_{ii}}{n_0}\right), \tag{1}$$

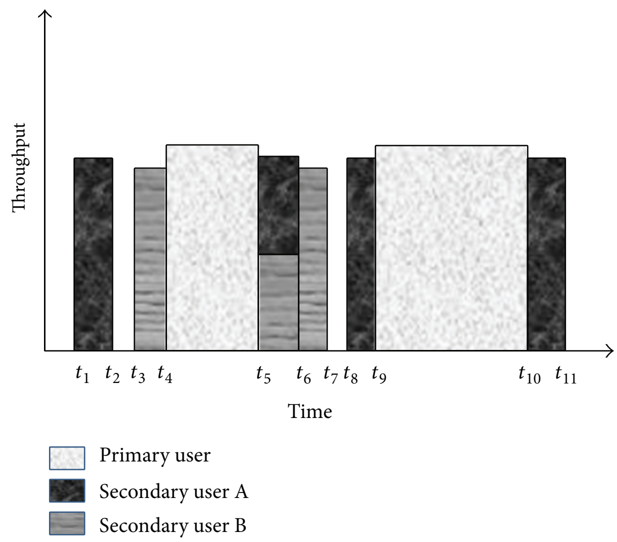


Figure 2: Throughput versus time [6].

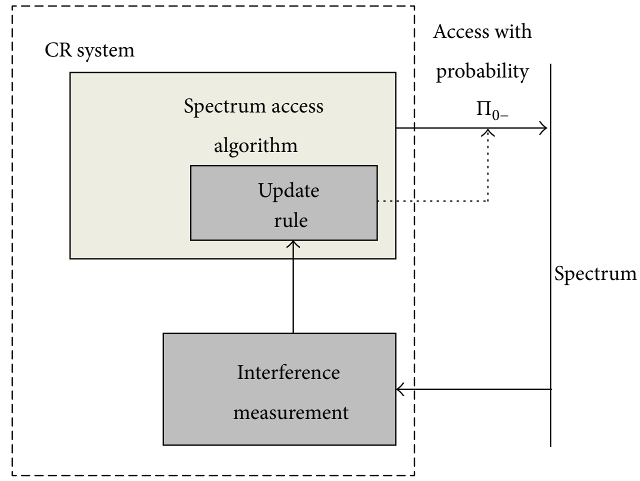


Figure 3: Distributed DSA system for the secondary user.

where W is the bandwidth, p_i is the transmission power for user i, G_{ii} is the channel gain for user i, and n_0 is the noise power. When the secondary users share the spectrum, the maximum data rate that can be achieved by any secondary user i, is given by [7, equation (2)]

$$R_2^i = W \log_2 \left(1 + \frac{p_i G_{ii}}{n_0 + \sum_{j \neq i} p_j G_{ji}} \right), \tag{2}$$

where G_{ji} is the channel gain from user j's transmitter to user i's receiver.

3. Distributed Primary Prioritized DSA Model

In this section, the overview of distributed DSA system and the CTMC model is presented.

3.1. Distributed DSA System. Distributed medium access schemes such as CSMA can be used for spectrum sharing. But CSMA requires that users have to back off for a random period of time when another user is transmitting. This requirement will not lead to efficient spectrum utilization in an unlicensed spectrum sharing scenario as it can result in the loss of transmission opportunities for the secondary users. Thus, spectrum utilization will be efficient if the incoming secondary user is allowed to transmit with interference instead of backing off. However, this interference should be properly controlled so that heavy contention does not cause excessive interference. To achieve this control, the behavior of primary and secondary users is modeled using CTMC which mathematically describes the interaction between them.

The distributed DSA system for the secondary users is shown in Figure 3. Each secondary user is equipped with a CR system. The system measures the interference encountered when two secondary users share the spectrum and accordingly modify the access probability using the distributed DSA algorithm and the update rules.

3.2. CTMC Model. In opportunistic spectrum access, the secondary users access the unoccupied primary spectrum and at the same time should vacate if primary appears. This is because the primary user has the highest priority to access the spectrum at any time. Hence, we model the primary-secondary interactions as a primary prioritized CTMC [7]. As the arrival rates of the secondary users are assumed to be independent Poisson process, exact arrival of service requests happens very rarely.

Figure 4 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 multiple secondary users as discussed in [7]. State S_0 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 S_0 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 S_0 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.

The probabilities in which the system is in any of these states can be computed from the infinitesimal matrix which is based on the arrival and service rates of the users. The infinitesimal generator matrix denoted by **Q** can be formed from the state transitions of the CTMC and given by

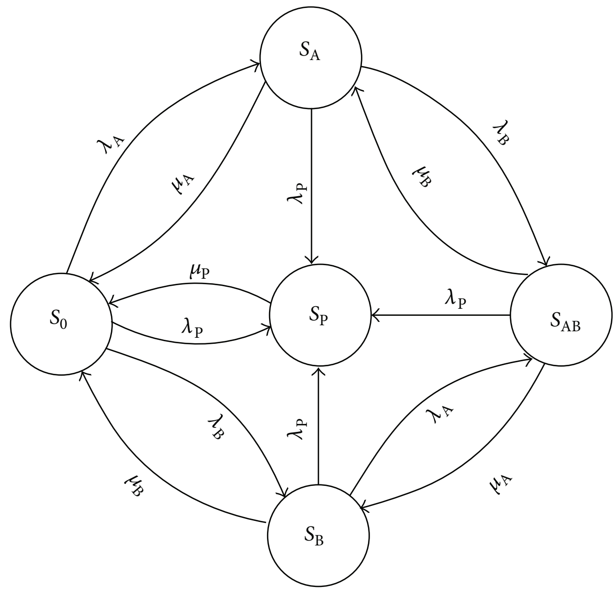


FIGURE 4: CTMC state transition diagram with perfect spectrum sensing.

$$Q = \begin{bmatrix} -(\lambda_A + \lambda_B + \lambda_P) & \lambda_A & \lambda_B & 0 & \lambda_P \\ \mu_A & -(\mu_A + \lambda_B + \lambda_P) & 0 & \lambda_B & \lambda_P \\ \mu_B & 0 & -(\mu_B + \lambda_A + \lambda_P) & \lambda_A & \lambda_P \\ 0 & \mu_B & \mu_A & -(\mu_B + \mu_A + \lambda_P) & \lambda_P \\ \mu_P & 0 & 0 & 0 & -\mu_P \end{bmatrix}. \quad (3)$$

We denote the vector containing the state probabilities by $\mathbf{\Pi}$ which is given by

$$\mathbf{\Pi} = [\Pi_0 \ \Pi_A \ \Pi_B \ \Pi_{AB} \ \Pi_P]. \quad (4)$$

We can solve the array [7] from

$$\mathbf{Q\Pi} = 0, \quad \sum \Pi = 1 \quad (5)$$

to obtain the state probability vector $\mathbf{\Pi}$.

Now, the overall throughput for any secondary user i is given by [7]

$$U_i = \Pi_i R_1^i + \Pi_{ij} R_2^i. \quad (6)$$

Thus, the CTMC model makes it easy—using the infinitesimal generator matrix [7] to calculate the probabilities of spectrum utilisation by the primary user and secondary users. More importantly, it is possible to directly calculate the probability, Π_0, using only the arrival rates and service rates of the users. The importance of Π_0 is that it is a function of all the other probabilities and therefore constitutes an easily computable parameter on the basis of which spectrum access decisions can be made by the secondary users.

3.3. CTMC Model with Access Control Probabilities. The CTMC model illustrated in Figure 5 includes access probabilities for secondary users. Access probabilities are those with which secondary users access the spectrum when it is being utilised by other secondary users. In other words, we can say that the access probabilities provide control over the amount of interference experienced by secondary users. The major challenge is to optimise these 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 the loss of transmission opportunities. In a centralised scheme, as in [7], this is done by acquiring the user statistics by a dedicated secondary management point, which then calculate the optimum access probabilities and communicate them to the corresponding secondary users. The secondary users stick to these access probabilities until there is a change in the statistics. However to do this distributively, without any communication between secondary users, we make a few simplifying assumptions and formulate heuristics on the basis of which secondary user statistics can be learned.

Assumption 1. The primary user statistics are known to all secondary users. The network service provider of a licensed user may, reasonably, be expected to have spectrum utilisation records and hence the usage statistics.

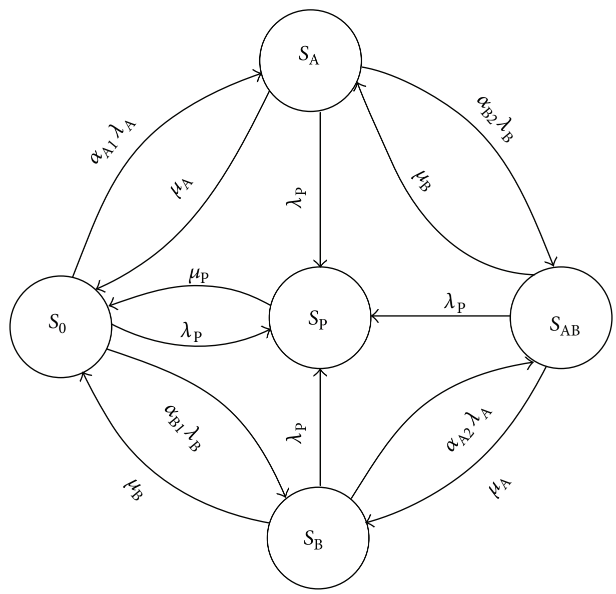


FIGURE 5: CTMC state transition diagram with access control probabilities [7].

Assumption 2. The statistics of the secondary users are comparable. That is, we expect the secondary users to possess similar behaviour patterns. If this is the case, a reasonable initialisation strategy would be that any secondary user assigns the initial estimate of the other secondary users as its own.

Heuristic 1. Interference for more than a certain fraction of time during a given transmission slot indicates an overestimated spectrum idle probability (Π_0), that is, 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. 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. The advantage of interfering has to be judged based on the likelihood of two events:

(1) rearrival of the transmitting secondary user during the service time of the incoming secondary user;

(2) arrival of primary user during the service time of the incoming secondary user.

Π_0, the spectrum idle probability, is a function of the probabilities of occurrence of both these events. This presents us with the possibility of using the Π_0 estimate of each secondary user as that user's access probability. Therefore, in the proposed scheme, we define the Π_0 estimate of a secondary user as its time-evolving access probability.

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 Π_0 estimate, Π_{0-}) 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).

$$\mathrm{IR} = \frac{T_i}{T}. \tag{7}$$

In Figure 5, the access probabilities for users A and B are denoted by (α_{A1}, α_{A2}) and (α_{B1}, α_{B2}), respectively. We assume that the access probabilities α_{A1} and α_{B1} are one, when the spectrum is found idle. The access probabilities α_{A2} and α_{B2} should be controlled to reduce the interference between the secondary users. The distributed algorithm to control these access probabilities based on the mutual interference experienced by the users is described in the following section.

4. Distributed Primary Prioritized Markovian Access Algorithm (DPMA)

The DPMA algorithm [15] designed on the basis of the above definitions and the previously formulated assumptions and heuristics are summarised in Algorithms 1 and 2.

The constants b_{1j} and b_{2j} represent the control parameters 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 $\mathrm{IR}_{\mathrm{ref}}$.

To evaluate the fairness of the distributed spectrum access scheme against variation in primary user spectrum utilization, a term called fairness factor is defined.

Definition 3. The Fairness factor (FF) is defined as the ratio of standard deviation of primary user spectrum utilisation over multiple instances to the standard deviation of overall spectrum utilisation of secondary users over the same number of instances.

$$\mathrm{FF} = \frac{\left[\operatorname{std}\left(U_p\right)/\operatorname{avg}\left(U_p\right)\right]}{\left[\operatorname{std}\left(U_s\right)/\operatorname{avg}\left(U_s\right)\right]}, \tag{8}$$

where U_p and U_s are PU spectrum utilization and overall SU spectrum utilization, respectively, std and avg are standard deviation and average values:

4.1. Distributed DSA Algorithm with Imperfect Sensing. It is more interesting to study the case when the sensing outcome of the secondary users is erroneous. We consider the effects of spectrum sensing errors in the form of false alarm and misdetection probabilities. The probability of false alarm (P_f) is defined as the probability that the spectrum sensing algorithm erroneously detects the presence of primary user when it is actually not present. Alternatively, the misdetection probability (P_{md}) is the probability that the spectrum sensing algorithm fails to detect the presence of primary user when it is actually present. On the other hand, the probability of

Distributed Primary-Prioritised DSA Algorithm

For each secondary user i,
(1) Initialize: $\lambda_{j\_} \leftarrow \lambda_i$; $\mu_{j\_} \leftarrow \mu_i$ for all $j \neq i$
(2) Calculate $\Pi_{0i\_}$ using (λ_p, μ_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 $\Pi_{0i\_}$. Else keep sensing.
(4) Sense the spectrum. If secondary user j $(j \neq i)$ is transmitting, then access the spectrum with a probability $\Pi_{0i\_}$.
(5) Update all $(\lambda_{j\_}, \mu_{j\_})$, $j \neq i$, based on the interference encountered during transmission (Refer update rule in Algorithm 2).

Algorithm 1: DPMA algorithm.

(1) Calculate the Interference Ratio (IR).
(2) If [IR $\geq$ IR$_{\text{ref}}$] Then go to Step 3 Else Step 4.
(3) $\lambda_{j\_} = \lambda_{j\_} + b_{1j}$; $\mu_{j\_} = \mu_{j\_} + b_{2j}$ for all $j \neq i$.
Go to Step 5.
(4) $\lambda_{j\_} = \lambda_{j\_} - b_{1j}$; $\mu_{j\_} = \mu_{j\_} - b_{2j}$ for all $j \neq i$.
(5) Recalculate $\Pi_{0i\_}$ using the estimates calculated in Steps 3 and 4 on the assumption that the other secondary users access the spectrum with a probability $\Pi_{0i\_}$ from the previous iteration.
(6) Use $\Pi_{0i\_}$ as the new access probability

Algorithm 2: Update rule.

correct decision is given by $1 - P_f$ or $1 - P_{\text{md}}$ corresponding to whether the secondary user senses correctly when the spectrum is free or occupied, respectively.

Accordingly, modified CTMC state diagram for imperfect sensing is shown in Figure 6. If the user A (or B) senses the absence of primary user correctly, the state transits from S_0 to S_{A} (or S_{B}) at a rate of $(1 - P_f)\lambda_{\text{A}}$ (or $(1 - P_f)\lambda_{\text{B}}$). If user A (or B) completes its service before any request from user B (or A), the CTMC transits to state S_0 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, primary user may appear anytime during either A's service or B's service or when both are sharing the spectrum. If the secondary users identify the arrival of primary user correctly, the CTMC transits to state S_{P} with a rate of $(1 - P_{\text{md}})\lambda_{\text{P}}$. If they misdetect the arrival of primary, the CTMC transits to state S_{PA}, S_{PB}, or S_{PAB} correspondingly with a rate of $P_{\text{md}}\lambda_{\text{P}}$. These three states represent the possibilities in which the primary user get interfered with the secondary user's communication and does not contribute to throughput. The probability that the CTMC is in these states should be avoided to protect the primary user from interference. This will be possible only if the probability of misdetection is very low. A suitable spectrum sensing algorithm may be used for primary signal detection to reduce the probability of misdetection. Thus, we see that the probability of false alarm reduces the spectrum access opportunities to the secondary user and the probability of misdetection cause interference to the primary users.

We denote the vector containing the state probabilities as $\mathbf{\Pi}$ which is given by

$$\mathbf{\Pi} = [\Pi_0\ \Pi_{\text{A}}\ \Pi_{\text{B}}\ \Pi_{\text{P}}\ \Pi_{\text{AB}}\ \Pi_{\text{PA}}\ \Pi_{\text{PB}}\ \Pi_{\text{PAB}}]. \quad (9)$$

The array can be solved as given in (5). The overall throughput of the secondary user can also be computed using (6).

The CTMC state transition diagram with access control probabilities for imperfect spectrum sensing is shown in Figure 7. The distributed primary prioritized DSA algorithm can also be modified to include the errors arising out of imperfect sensing. To control the throughput degradation arising out of imperfect sensing, the access probabilities are provided to the secondary users whenever they try to access the spectrum. Here, the access probabilities of secondary users A and B are denoted by α_{A} and α_{B}.

Thus, we verify by numerical simulations that the performance of the distributed DSA system with self-learned access control probabilities follows the theoretical results, and it is also comparable to that of the results achieved for maximum throughput criterion in [7]. It can also be verified that the performance of the system with imperfect spectrum sensing is greatly affected as the sensing error probabilities increase.

5. Simulation Results and Analysis

Simulation parameters are chosen as follows. As in [7], we set the bandwidth of the licensed spectrum as $W = 200$ kHz, the transmission power for the secondary users $p_i = 2$ mW, the noise power $n_0 = 10^{-15}$ W, and the path loss exponent as 2. Spectrum occupancy measurements [16] show that licensed users typically utilise the spectrum about 45% of the time. Accordingly, we set the arrival rate, service rate pair of the primary user (λ_p, μ_p) to $(85, 100)\,\text{s}^{-1}$. The arrival rate of secondary user B is assumed to be $\lambda_{\text{B}} = 85\,\text{s}^{-1}$ and the arrival rate of secondary user A λ_{A} is $70\,\text{s}^{-1}$ for fixed arrival rate or

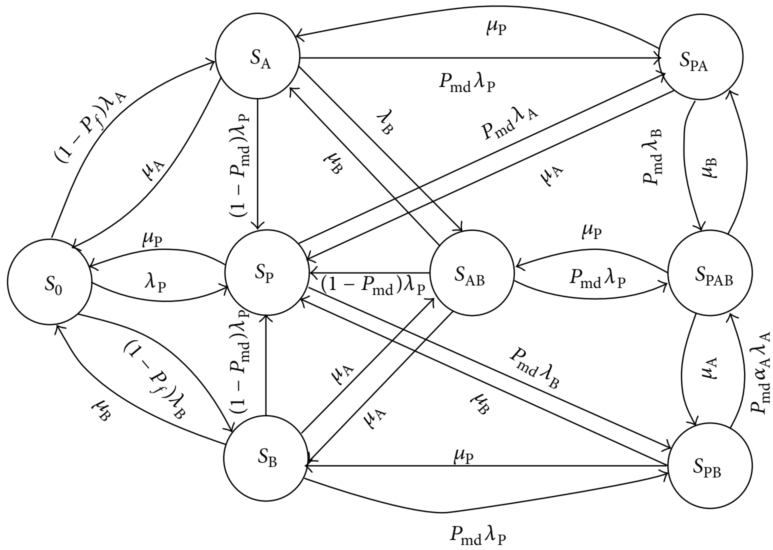


Figure 6: CTMC state transition diagram with imperfect spectrum sensing.

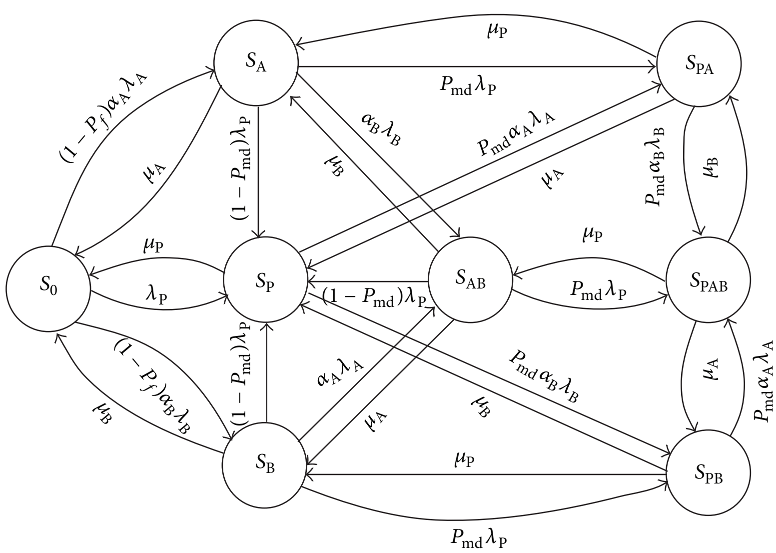


Figure 7: CTMC state transition diagram with access control probabilities.

varied from 70 to 100 s^{-1} for variable arrival rate analysis. The departure rates of both secondary users are set to 100 s^{-1}.

5.1. Throughput Analysis for DPMA Scheme (Fixed Arrival Rates). We analyze the throughput performance of the primary user and both the secondary users using the CTMC model. The locations of the secondary users are assumed to be symmetric and are as follows: user A's transmitter at (0 m, 0 m) and receiver at (200 m, 0 m), user B's transmitter at (200 m, 460 m) and receiver at (0 m, 460 m). As in [7], we compare the performance of the proposed scheme with the persistent form of CSMA. For the update rule in the algorithm, both b_{1j} and b_{2j} are set to 10. IR_{ref} is set to 0.1 (assuming a maximum of 10% tolerance as interference). The results on running the simulations with these parameters for a period of 3 s are tabulated in Tables 1 and 2. All the throughput values are expressed in % of R_{max} which is the maximum achievable throughput for the users. It is clear that the proposed algorithm achieves considerable increase in overall throughput and provides better fairness among the secondary users over CSMA.

The average throughput histograms of secondary users obtained for 100 independent experiments are also shown in

Table 1: Average throughput per secondary user using DPMA and CSMA schemes.

Spectrum access algorithm	User 1 throughput (in % R_{max})	User 2 throughput (in % R_{max})	Overall throughput (in % R_{max})
CSMA	17.80	23.10	40.90
DPMA	19.78	25.87	45.65

Table 2: Average throughput with maximum and std values for DPMA and CSMA schemes.

Spectrum access algorithm	Average throughput per secondary user (in % R_{max})		
	Average	Maximum	Standard deviation (std)
CSMA	20.45	25.13	2.63
DPMA	22.83	25.62	1.77

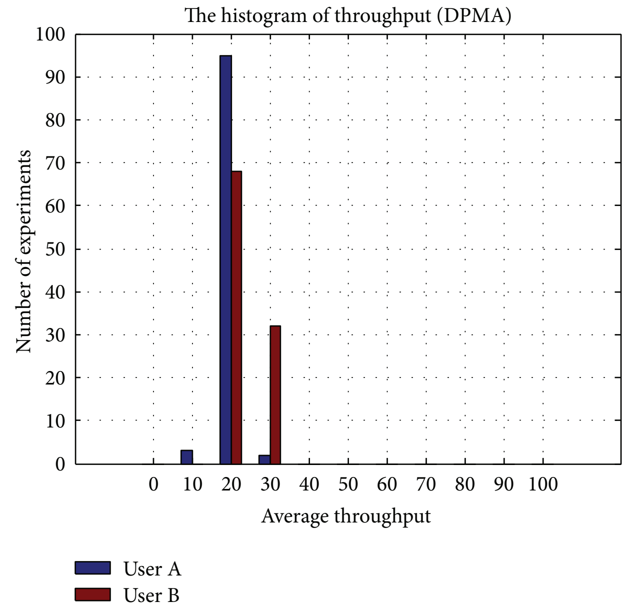


Figure 8: Histogram of throughput versus number of experiments using DPMA.

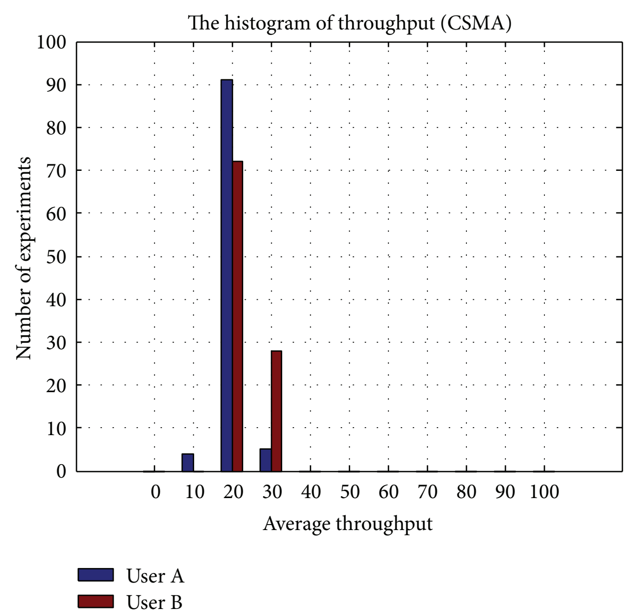


Figure 9: Histogram of throughput versus number of experiments using CSMA.

Figures 8 and 9 for both the proposed DPMA and CSMA scheme. It is inferred that the proposed DPMA scheme achieves higher average throughput than the CSMA-based scheme.

The FFs for the two schemes CSMA and DPMA are computed as 1.00 and 1.79, respectively, using (8). Thus, DPMA has a greater ability to maintain the overall throughput of secondary users against variation in primary user spectrum utilisation and is a fairer scheme compared to CSMA.

We then analyze the access probability variations of the proposed DPMA scheme. The initialisation strategy we adopt ensures a certain degree of fairness in spectrum access, or equivalently throughput between two secondary users with different arrival rates. For instance, if the arrival rate of secondary user A is $70\,\mathrm{s}^{-1}$ and user B is $85\,\mathrm{s}^{-1}$ and if the users follow DPMA scheme, then user A initially assumes the arrival rate of user B as $70\,\mathrm{s}^{-1}$. Similarly, user B initially assumes the arrival rate of user A to be $85\,\mathrm{s}^{-1}$. Thus, user A overestimates Π_0, while user B underestimates it. These estimates are also the access probabilities of the secondary users. Therefore, over the first few instants of time (or equivalently the first few iterations), user A accesses the spectrum with a higher probability than user B. That is, the user with the low arrival rate is initially allowed a higher access probability than the user with a high arrival rate. Over time, user A is likely to experience more interference than user B. Based on the interference encountered, both users update their estimates and recalculate their access probabilities. After the first few iterations, the access probability of user B goes up while that of user A goes down as expected. This is shown in Figure 10.

In Figure 11, the total throughput achieved for varying number of secondary users is plotted using DPMA algorithm. It can be observed that the total throughput does not increase much as the number of secondary user increases because the spectrum has to be shared with more number of secondary users.

5.2. Throughput Analysis for DPMA Scheme with Perfect Sensing (Variable Arrival Rates). In Figure 12, the throughput variation of the secondary users for varying arrival rate for user A (from 70 to $100\,\mathrm{s}^{-1}$) is shown. The arrival rate of user B is fixed at $85\,\mathrm{s}^{-1}$. Initially when $\lambda_A < \lambda_B$, the throughput of user B is higher than that of user A, and as λ_A increases such that $\lambda_A < \lambda_B$, the throughput of user A increases. This is because when the arrival rate of user A is lower, its average access probability is lower than the average access probability of user B. Thus, the average throughput is lower than that of user B. It is also verified that the simulation results using DPMA spectrum scheme follows the results obtained theoretically using the CTMC model.

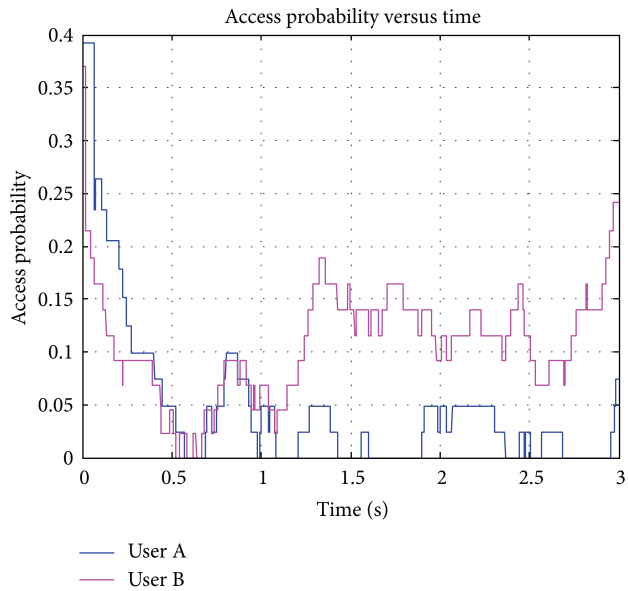


Figure 10: Access probability variations versus number of iterations.

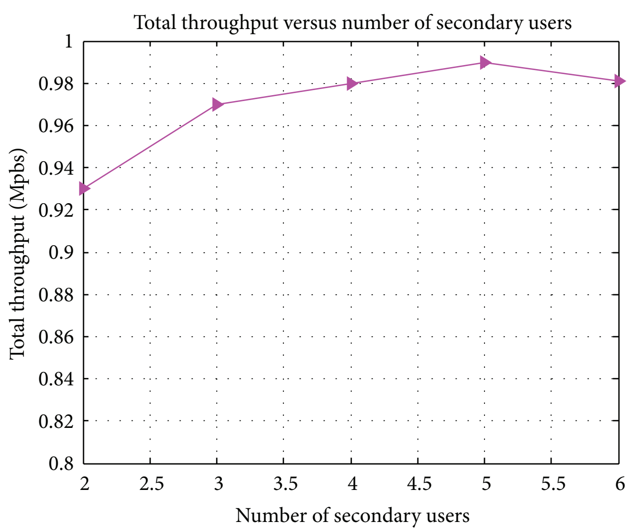


Figure 11: Total throughput versus number of secondary users.

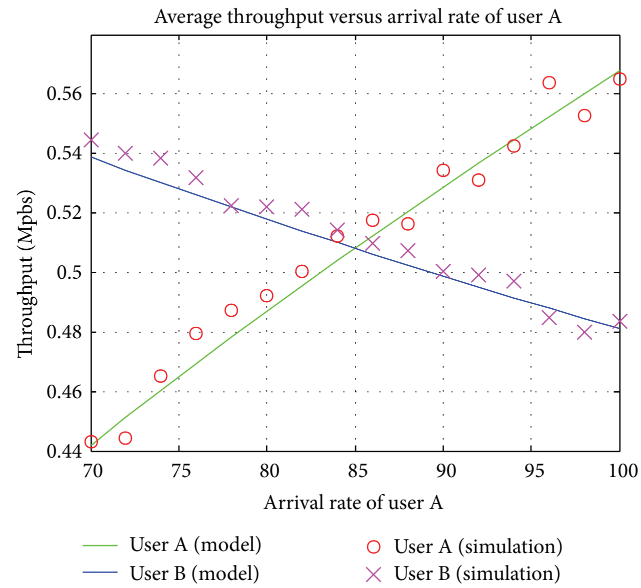


Figure 12: Throughput versus arrival rate λ_A ($\lambda_B = 85\,s^{-1}$) with perfect sensing.

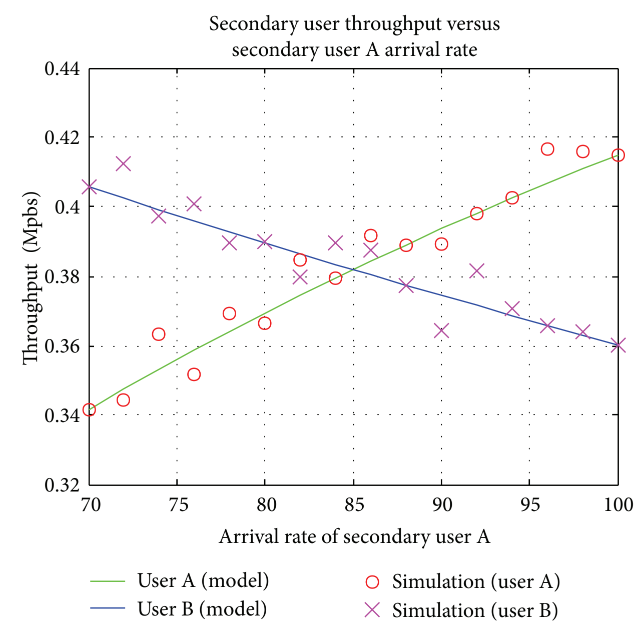


Figure 13: Throughput versus arrival rate λ_A ($\lambda_B = 85\,s^{-1}$) with imperfect sensing.

5.3. Throughput Analysis for DPMA Scheme with Imperfect Sensing (Variable Arrival Rates). The secondary user throughput is also analyzed for imperfect sensing scenario. As expected, the average secondary user throughput is reduced compared to the ideal scenario. The simulation results using the DPMA scheme follow the results achieved using the CTMC model and are shown in Figure 13.

5.4. Primary User Spectrum Utilization. This analysis shows the throughput degradation caused to the primary users because of misdetection. Misdetection probability can cause heavy degradation in throughput for the primary users because of the interference caused to them. When the secondary users fail to notice the presence of primary users, it tries to access the licensed spectrum and causes harmful interference to them. This is represented as the states S_{PA}, S_{PB}, and S_{PAB} in the CTMC state transition diagram (Figure 4), which does not contribute to throughput. Figure 14 shows the decrease in the primary user channel utilization with respect to increase in the probability of misdetection.

5.5. Spectrum Utilization with Imperfect Sensing. The variation in both the primary user and the secondary user spectrum utilization with respect to increasing false alarm is observed. As expected, false alarm causes loss in transmission

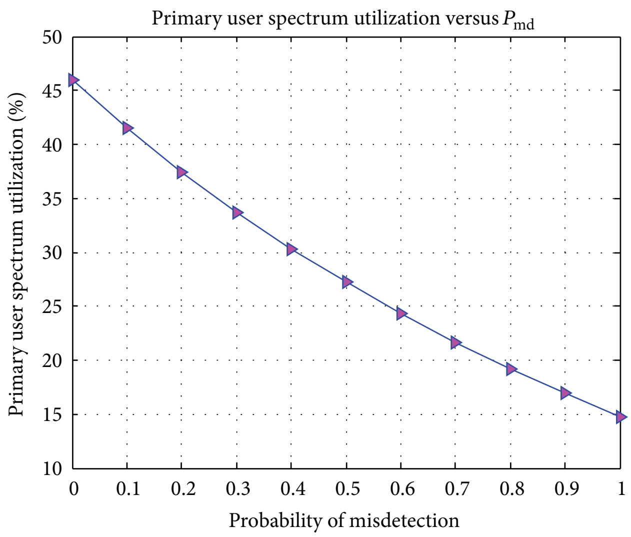


FIGURE 14: Primary user spectrum utilization versus P_{md}.

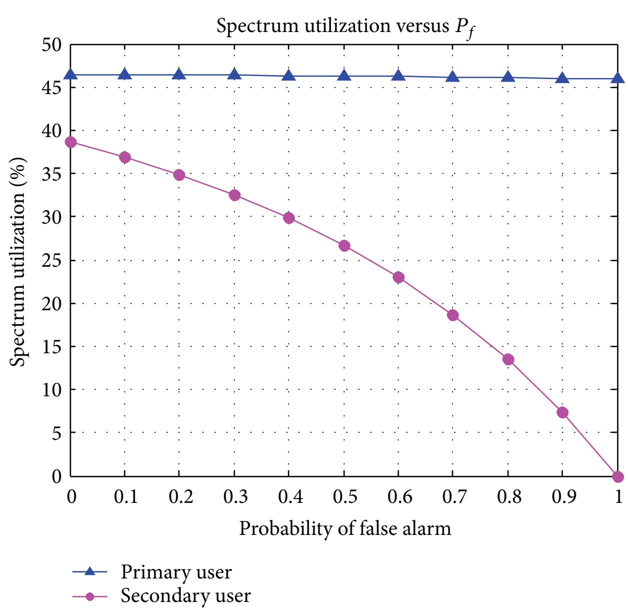


FIGURE 15: Spectrum utilization versus P_f.

opportunities for the secondary users, and thus secondary user's utilization decreases with increase in false alarm probability. As false alarm does not cause interference to the primary users, the spectrum utilization of the primary user remains constant for the variations in the false alarm as shown in Figure 15.

6. Conclusions

In this paper, a distributed DSA algorithm was proposed using CTMC model of interactions between the primary user and secondary users. This is a first step towards the completely distributed approach on CTMC-based DSA algorithm. This scheme is completely primary prioritized and also considers the effects of imperfect sensing in the form of misdetection and false alarms. Using the proposed approach, we showed that the average throughput of the secondary users is better compared to CSMA-based scheme and also produces fair throughput distributions. We also studied the throughput degradation caused to primary and secondary users due to imperfect spectrum sensing. Extending our scheme to multiple secondary users will be an interesting future work. Another interesting extension will be adaptively updating the parameters of the algorithm.

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