Opportunistic Spectrum Access in Cognitive Radio Networks Under Imperfect Spectrum Sensing

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***Abstract*—In this paper, we investigate the effect of imperfect sensing on the performance of opportunistic spectrum access (OSA) in cognitive radio networks. We consider a system modeled as a continuous-time Markov chain (CTMC), and then evaluate its performance in terms of the probabilities of users being blocked or dropped. Our results demonstrate that the performance of the underlying system degrades significantly when imperfect sensing is considered; thus, there is a pressing need for a reliable spectrum sensing scheme to improve the overall quality of service in practical scenarios. A simulation study is presented to corroborate the analytical results and to demonstrate the performance of OSA under imperfect sensing conditions.**

***Index Terms*—Access control, cognitive radio, continuous time Markov chain, spectrum sensing, spectrum management, utilization.**

I. Introduction

THE need for efficient utilization of the spectrum has become a fundamental requirement in modern wireless networks, which is due mainly to spectrum scarcity and the ever-increasing demand for higher data rate applications and internet services. A particularly interesting proposal is the development of cognitive radio (CR) networks that can adapt their transmission parameters according to the environment. Cognitive radios have been shown to be very efficient in maximizing spectrum utilization due to their inherent spectrum sensing capability. In a cognitive radio network environment, different users can be categorized as primary users (PUs), representing users having higher priority, and secondary users (SUs), representing those users wishing to opportunistically access the spectrum by sensing the channels already used for transmission.

Three detection techniques are commonly used for spectrum sensing in CRs, namely, energy detection, [1], [2], matched filters, [3], and cyclostationary detection [4]. In energy detection, which is the most common technique due to its low implementation complexity, the presence of a PU signal is detected simply by comparing the output of the energy detector with a certain threshold. Different energy based approaches have been proposed to improve the detection of spectrum holes (SHs): namely, cooperative sensing [5], beamforming [6] and the multiple antenna approach [7], [8].

In spectrum sensing, however, there are always errors. Two errors which inevitably occur and which are of particular interest here are misdetection and false alarm errors, which quantify the amount of interference to the PU and the overlooked SHs in the system, respectively. It should be noted that there exists a fundamental tradeoff between the two errors, since they are inversely related.

A. Related Works and Contributions

The spectrum access in cognitive radio networks has received a substantial attention by the researchers and has been considered widely in the literature as reported in [9], [10], and the references listed there in. However, most of the work reported in the literature on spectrum access is performed under the assumption of prefect spectrum sensing, which might be misleading in practical scenarios.

Recently, Tang *et al.* [11] studied the opportunistic spectrum access (OSA) system under unreliable sensing. In this work, the SUs were assumed to sense only one channel at a time to determine the access probability. However, a fundamental requirement for an SU is to sense a wide band of the spectrum to have a reasonable access opportunities and reliable transmission [12]. Such sensing ability enables the SU to continue its transmission when a PU requests, with no warning, a channel that

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is already occupied by an SU. The problem of switching channels or spectrum handoff under unreliable sensing and prioritized traffic was studied in [13]. In [14], the modeling of opportunistic spectrum access under unreliable sensing was studied. However, the authors again consider that an SU can only sense one channel at a time. In addition, only cases where SU calls are blocked are considered. We will discuss this further later.

In this paper, we consider that the SUs have the ability to sense all channels in the system. The result reported by [11] suggests that spectrum efficiency can be improved even under unreliable sensing; however, our analytical and simulation results confirm that the SUs must be equipped with a reliable sensing function to fully exploit spectrum opportunities. Cooperative sensing does improve the detection of an SH; however, sensing errors still cannot be avoided as they can occur at any time. Although cooperative sensing is not considered in this work, extending the analyses for such scenarios is straightforward.

Since sensing errors may occur at random, the objective of this work is to analyze and evaluate OSA in terms of a number of performance metrics when imperfect sensing by SUs is considered; specifically, we derive the probability of blocked and dropped calls for the primary and secondary systems under imperfect sensing. Moreover, we evaluate the secondary system utilization when sensing errors occur. Finally, closed-form expressions for all of the mentioned metrics under perfect and imperfect sensing are derived.

The rest of the paper is organized as follows. In Section II, we briefly discuss the spectrum sensing model. The system description and Markov chain modeling with perfect/imperfect sensing are presented in Section III. The simulation results are discussed in Section IV, and the paper is concluded in Section V.

II. Spectrum Sensing Model

Spectrum sensing is a binary hypothesis problem, which distinguishes between two hypotheses defined as [15]

$$\begin{aligned} H_0: &\quad x(t) = w(t) \\ H_1: &\quad x(t) = s(t) + w(t) \end{aligned} \tag{1}$$

where H_0 is the hypothesis test when noise only is present, H_1 is the hypothesis test when both noise and signal are present, $w(t)$ is the noise component, and s(t) is the primary user signal component. Evaluating test Y, which is defined as $Y = \frac{1}{N_o}\int_0^T x(t)^2 dt$, where N_o represents the one-sided noise spectral density, may cause two types of errors. When an SU detects H_1 while the actual state is H_0, this event is called a false alarm which occurs with a probability denoted by $P_{fa} = P(H_1|H_0) = Q\left(\frac{\lambda - 2B}{\sqrt{4B}}\right)$, where $Q(.)$ is the tail probability of the standard normal distribution, B is the time bandwidth product, λ is the detection threshold and γ is the signal-to-noise ratio (SNR).[1] When an SU detects H_0 while the actual state is H_1, this event is called misdetection which occurs with a probability denoted by $P_m = P(H_0|H_1) = 1 - Q\left(\frac{\lambda - 2B - \gamma}{\sqrt{4(B+\gamma)}}\right)$. The complementary to P_m is the probability of detection $P_d = 1 - P_m = P(H_1|H_1)$.

III. Markov Chain Modeling

Consider a system of C channels, where all channels are available to the PUs. Access is controlled by the primary controller, and the system is opportunistically available to secondary users when PUs are absent. From a practical point of view, the PUs, also known as licensed users, are unaware of the activity of the SUs, also known as unlicensed users; therefore, a PU may use a channel already occupied by an SU, causing the SU transmission to drop. The drop occurs because of a lack of communication between the two systems or an unwillingness to modify the infrastructure of the PU system due to cost. The SUs, however, maintain an awareness of the PUs activity by employing a sensing function and transmitting whenever a channel is available.

We assume the arrival rate of PUs and SUs follows a Poisson process with arrival rates of λ_p and λ_s, respectively. The service time is exponentially distributed with mean service times $1/\mu_p$ and $1/\mu_s$ respectively. These assumptions are valid considering that the number of users is much greater than the number of available channels [11], [16]. Consider the general state (i, j), where i represents the number of PUs and j represents the number of SUs. Fig. 1 summarizes the transition states, under perfect sensing, of a PU arrival/departure denoted by the solid line, and an SU arrival/departure denoted by the dotted line.

A. Perfect Sensing

The following cases describe the system behavior when a PU arrives:

- Case I: A PU arrives and finds an idle channel not occupied by any other PU. The probability of this event is equal to $\frac{C-i-j}{C-i}$; therefore, the transition rate

[1] For large number of samples and using the central limit theorem, the distribution of test Y can be approximated as Gaussian [15].

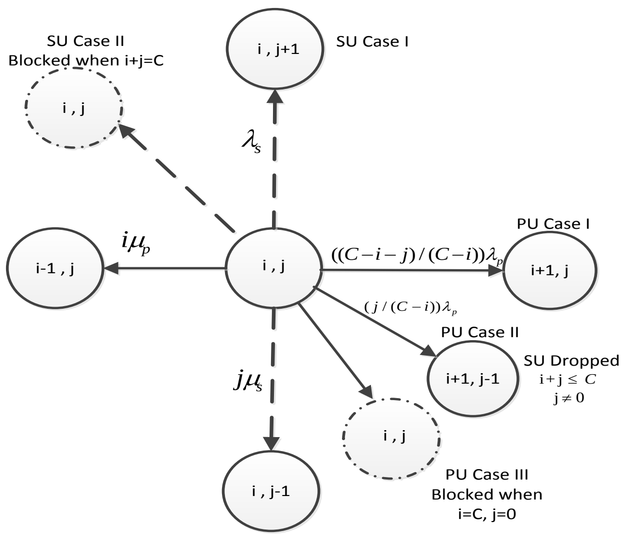

Fig. 1: Transition diagram under ideal sensing.

from state (i,j) to $(i+1,j)$ is given as $\frac{(C-i-j)}{(C-i)}\lambda_P$ [17].

- Case II: A PU chooses a channel occupied by an SU, which causes a collision with the SU transmission; in this case, the transition rate from state (i,j) to state $(i+1,j-1)$ will be $\frac{j}{C-i}\lambda_p$, and the total probability of a dropped SU call can be computed as

$$P_{drop,SU} = \sum_{\substack{i,j \\ i+j \le C}} \frac{j\lambda_p}{(C-i)\lambda_s}. \tag{2}$$

- Case III: A PU arrives and all channels in the system are occupied by other PUs, i.e., $i = C, j = 0$; in this case, the new PU request will be blocked. Hence, the probability of a PU being blocked is given by

$$P_{block,PU} = P(C,0) \tag{3}$$

where $P(i,j)$ is the steady-state probability of state i,j.

Now we consider an SU arrival, which can be described by the following cases:

- Case I: An SU arrives and a channel is available; therefore, the transition rate from state (i,j) to state $(i,j+1)$ is λ_s, for $i+j<C$.
- Case II: An SU arrives and no channel is available, resulting in a blocked request; therefore, an SU request will be blocked only when $i+j=C$, and the probability of a blocked SU is given by

$$P_{block,SU} = \sum_{\substack{i,j \\ i+j=C}} P(i,j). \tag{4}$$

All other cases, i.e. with no PU or SU arrival, are considered to be successfully completed, hence the PU departure rate from state (i,j) to $(i-1,j)$ is $i\mu_p$. Likewise, the SU departure rate from state (i,j) to state $(i,j-1)$ is given as $j\mu_s$.

If we define $s=(i,j)$ as the instantaneous state of the continuous-time Markov chain (CTMC) model presented in Fig. 1, then it has the state space:

$$\Omega = \{s : 0 \le i,j \le C, i+j \le C\}.$$

The system of linear equations which is formed from the Markov chain model can be written in vector-matrix form as

$$\mathbf{pQ} = \mathbf{0} \tag{5}$$

where $\mathbf{p}$ is the steady-state probability vector, and $\mathbf{Q}$ is the infinitesimal generator matrix which characterizes the transition of the states of the Markov chain. To yield a unique positive solution, (5) can be solved with the imposed normalization condition of the steady state probability, which is defined as

$$\sum_i \sum_j P(i,j) = \mathbf{p1} = 1 \quad \forall (i,j) \le C \tag{6}$$

where $\mathbf{1} = [1,1,1,...,1]^T$, (the superscript T indicates the transpose operation). Hence, the steady state probability vector $\mathbf{p}$ can be found by changing the last column of $\mathbf{Q}$ by the vector $\mathbf{1}$, which yields the new invertible matrix $\mathbf{Q}'$, i.e. (5) becomes $\mathbf{pQ}' = \mathbf{b}$, where $\mathbf{b}$ is a row vector which was formed by this operation, i.e. $\mathbf{b} = [0,0,...,1]$. Then, $\mathbf{p}$ can be found as

$$\mathbf{p} = \mathbf{bQ'^{-1}}. \tag{7}$$

The dimension of the matrix $\mathbf{Q}$ in terms of C is given as $[(C+1)(C+2)/2, (C+1)(C+2)/2]$. It follows then, and by using (7), Equations (2), (3) and (4) can easily be evaluated in the ideal sensing case. In what follows, we will evaluate the system with imperfect sensing results.

B. Imperfect Sensing

The probability that an SU detects an idle channel is the probability that it detects H_0 when H_0 is true, denoted as $\beta = P(H_0|H_0) = 1 - P_{fa}$, which is the complement of the false alarm probability. Since the PUs are not aware of the SUs, then the transition diagram shown in Fig. 1 will be modified only for cases in which an SU arrives. Before analyzing the proposed system with respect to an SU arrival under imperfect sensing, we should note that at any time the number of available channels in the system will be $N_{av} = C - N_{oc}$, where N_{oc} is the total occupied channels and is given as $N_{oc} = i + j$. Then, the probability of an arriving

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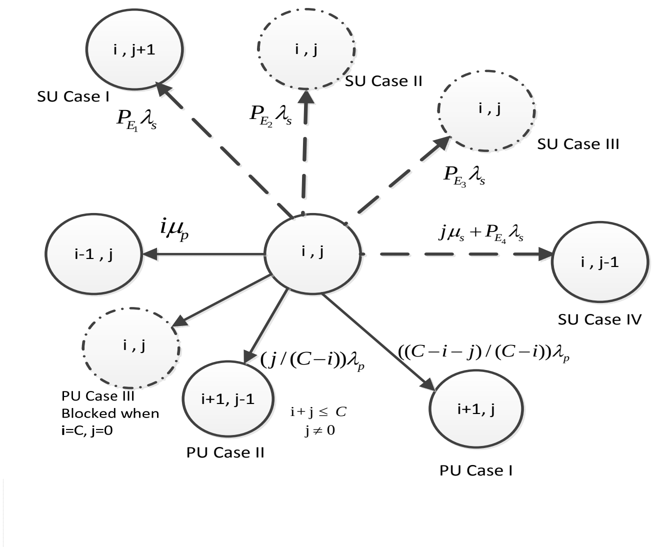

Fig. 2: Transition diagram under imperfect sensing.

SU sensing l busy channels of the occupied channels incorrectly is given as $\binom{N_{oc}}{l} P_d^{N_{oc}-l} P_m^l$.[2] Among the available channels, the probability of an SU sensing k idle channels correctly is $\binom{N_{av}}{k} {P_{fa}}^{N_{av}-k} \beta^k$. As we considered earlier that the system is in the general state (i,j), the following summarizes all of the SU arrival cases it may face:

- Case I: An SU arrives and there is no collision with a PU or other SUs. We denote this event as E_1, and the probability of this event can be computed as

$$P_{E_1} = \sum_{k=1}^{N_{av}} \binom{N_{av}}{k} \beta^k P_{fa}^{N_{av}-k} \sum_{l=0}^{N_{oc}} \frac{k}{l+k} \binom{N_{oc}}{l} P_d^{N_{oc}-l} P_m^l. \tag{8}$$

The transition rate from state (i,j) to state $(i,j+1)$ is then $P_{E_1}\lambda_s$.

- Case II: An SU arrives and all channels are busy. We represent this event by E_2 and its probability is given by

$$P_{E_2} = P_d^{N_{oc}} (1-\beta)^{N_{av}}. \tag{9}$$

The total probability of an SU being blocked with imperfect sensing will be[3]

$$P^*_{block,SU} = \sum_{i,j} P(i,j) P_{E_2}(i,j). \tag{10}$$

- Case III: An SU arrival interferes with a PU transmission due to a sensing error in detecting a PU occupied channel; we denote this event by E_3. The probability of this event will be the probability of wrongly detecting a channel already occupied by a PU or an SU and the probability of right-detecting the actual available channels N_{av}, i.e., mathematically we can write the probability of this event as

$$P_{E_3} = \sum_{k=1}^{i} \binom{i}{k} P_d^{(i-k)} P_m^k \sum_{n=0}^{j} \binom{j}{n} P_d^{(j-n)} P_m^n \times \sum_{l=0}^{N_{av}} \frac{k}{l+n+k} \binom{N_{av}}{l} P_{fa}^{(N_{av}-l)} \beta^l. \tag{11}$$

The rationale for (11) is that the SU cannot distinguish between an SU transmission and a PU transmission. In this case, the arriving SU will be dropped and the probability of a dropped call due to this event is given as

$$P^*_{drop_{E_3},SU} = \lambda_s P_{E_3}/\lambda_s = P_{E_3}. \tag{12}$$

Note that the system will stay in its current state and no transition occurs here.

- Case IV: An SU arrives and collides with another SU transmission. We denote this event by E_4. Thus, the probability of this event can be computed as in event E_3, and is given as

$$P_{E_4} = \sum_{k=1}^{j} \binom{j}{k} P_d^{(j-k)} P_m^k \sum_{n=0}^{i} \binom{i}{n} P_d^{(i-n)} P_m^n \sum_{l=0}^{N_{av}} \frac{k}{l+n+k} \binom{N_{av}}{l} P_{fa}^{(N_{av}-l)} \beta^l. \tag{13}$$

The probability of a dropped call due to this event will then be

$$P^*_{drop_{E_4},SU} = \lambda_s P_{E_4}/\lambda_s = P_{E_4}. \tag{14}$$

Hence the transition rate from state (i,j) to state $(i,j-1)$ will be $j\mu_s + P_{E_4}\lambda_s$, where the first term indicates an SU successfully completed its transmission and the second term indicates a dropped call caused by a collision between two SUs.

To compute the total probability of a dropped call in the secondary system in the current state (i,j), we add the probability of a dropped call for all events that cause an arriving SU to be dropped. Therefore, the total probability of a dropped call in the current state will be

$$P^*_{drop,SU} = P_{E_3} + 2P_{E_4} + \frac{j\lambda_p}{(C-i)\lambda_s} \tag{15}$$

[2] the symbol $\binom{n}{m} = \frac{n!}{m!(n-m)!}$

[3] To reduce the excessive use of notation, we distinguish the probabilities and all related parameters of imperfect sensing by an “*".

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where the first term represents a collision with a PU, the second term represents a collision between two SUs (the new arrival and the already connected SUs), and the third term represents a dropped call caused by a PU arrival (PU case II). Fig. 2 summarizes the potential transitions with imperfect sensing results. Using the previous discussion and the transition diagram of Fig. 2, we can reconstruct the infinitesimal generator matrix $\mathbf{Q}$ due to imperfect sensing. Following the same procedure discussed earlier and after modifying the transition matrix $\mathbf{Q}$, we can solve for the steady state probability using (7). To account for the total probability of a dropped call in the secondary system, we use (15). The total probability of a dropped call can then be computed as

$$P^*_{drop,SU} = \sum_{i,j} P(i,j)[P_{E_3}(i,j) + 2P_{E_4}(i,j) + \frac{j\lambda_p}{(C-i)\lambda_s}]. \quad (16)$$

Since dropped and blocked services do not count as successful radio traffic, another performance metric of importance to the considered secondary system is the effective spectrum utilization U, which is defined as

$$U = [1 - P^*_{block,SU} - P^*_{drop,SU}]\rho/C \quad (17)$$

where $P^*_{block,SU}$ is total blocked probability as defined in (10), $P^*_{drop,SU}$ is the total dropped probability as defined in (16) and ρ is defined as $\rho = \lambda_s/\mu_s$. Using this definition we account for only the actual SU traffic served by the considered system.

IV. Simulation Performance and Results Discussion

An event-based simulation using Matlab was used to evaluate and verify the theoretical results. Assuming $C = 10$, $\lambda_p = 2.15$ min^{-1}, $\mu_p = 0.5$ min^{-1} and $\mu_s = 5$ min^{-1}, Fig. 3 shows a comparison between the theoretical results and the event-based simulation results in the ideal sensing situation. We plot $P_{block,PU}$, $P_{block,SU}$ and $P_{drop,SU}$, which correspond to equations (2)-(4) respectively, versus λ_s. As a function of λ_s, $P_{block,PU}$ remains constant and coincides with the theoretical finding as the traffic load λ_p/μ_p for the primary system is fixed and the primary system has higher precedence than the secondary system. Having a closer look at $P_{block,SU}$ and $P_{drop,SU}$, the former is an increasing function of λ_s; the greater the arrival rate of SUs, the more likely they will be blocked, as SUs have lower precedence. However, the latter will slightly decrease by increasing λ_s. We should also note that the probability of a dropped call is initially higher than the probability of a blocked call

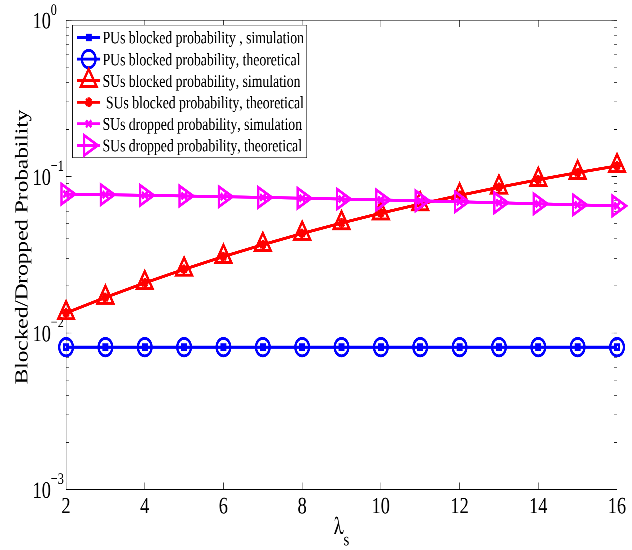

Fig. 3: Blocked/Dropped probability: Comparison between simulation and theoretical probabilities under perfect sensing.

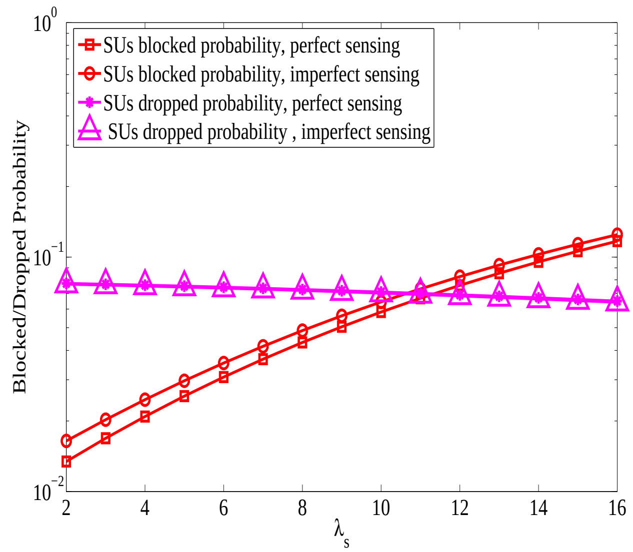

Fig. 4: Blocked/Dropped probability: Comparison between perfect and imperfect sensing with SNR = -5 dB, $P_{fa} = 0.1$, and $\mu_s = 5$.

for the secondary system; however, a point is reached where dropping becomes less severe than blocking. The reason for this behavior is that the greater the number of calls being blocked, the less probability there is of having SUs collide with PUs or other SUs in the system, which causes them to be dropped.

To evaluate the effect of imperfect sensing on the considered system, extensive simulations were conducted by changing various parameters. Fig. 4 shows a comparison

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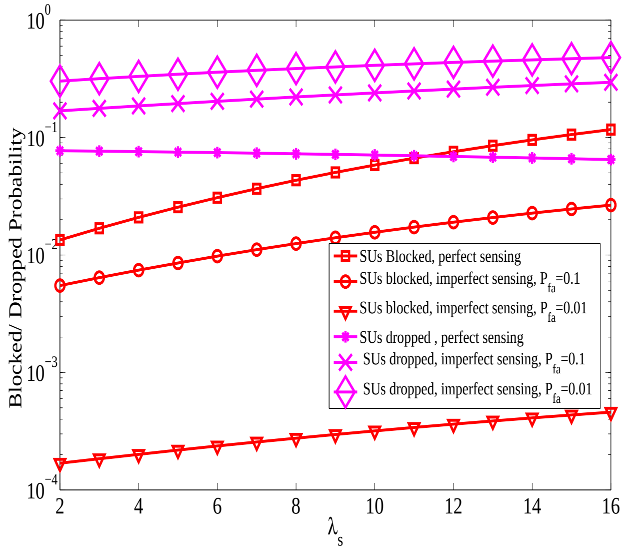

Fig. 5: Blocked/Dropped probability: Comparison between perfect and imperfect sensing with SNR = -10 dB, and $\mu_s = 5$.

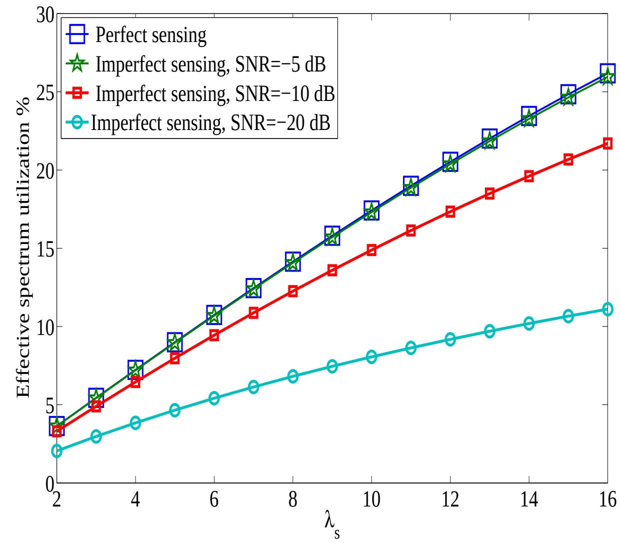

Fig. 6: Secondary system utilization: Comparison between perfect and imperfect sensing with different values of SNR, $P_{fa} = 0.1$, $\mu_s = 5$.

between perfect and imperfect sensing, with SNR = -5 dB, $P_{fa} = 0.1$, and the number of samples equaling 200. It can be seen that the probability of a dropped call is not affected at all by imperfect sensing, as fewer collisions with PUs and/or SUs occur due to the higher detection probability. On the other hand, the probability of a blocked call is higher than in the ideal sensing case, and this is due to the effect of the probability of false alarms.

In order to detect the very low level of a PU signal, the SU must have a sensitivity as much as 20-30 dB higher than that of the PU [18]. Therefore, in Fig. 5, two cases are studied. In the first case, we have reduced the SNR value to -10 dB and have kept the $P_{fa} = 0.1$ to see the effect of reducing the detection performance of the system. As expected the probability of a dropped call is considerably increased, as more collisions with PUs and SUs occur due to events E_3 and E_4. The unexpected result is the reduction of the probability of blocked calls and that can be explained as follows. Since the probability of dropped calls increases, more already connected SUs are dropped. This results in the availability of more channels to incoming SUs. The more channels are available, the lower the probability of event E_2 occurring; as a consequence, the probability of a call being blocked is reduced as seen in (10). In the second case, we have kept the SNR at -10 dB and have decreased $P_{fa} = 0.01$. It can be seen in Fig. 5 that the dropped probability slightly increased as reducing false alarms increases the misdetection probability, which then causes more collisions between PUs and SUs. However, the blocked probability is considerably decreased. The reason for the decrease is that more dropped calls allows more channels to be available to newly arrived SUs, and also reduces false alarms allowing the SUs to be more aggressive. This results in fewer occurrences of event E_2 and therefore the number of blocked calls is reduced.

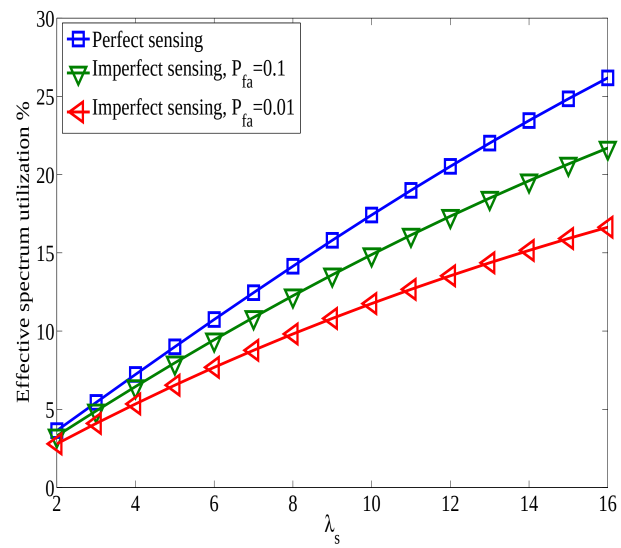

Fig. 7: Secondary system utilization: Comparison between perfect and imperfect sensing with different values of P_{fa}, $\mu_s = 5$, and SNR = -10 dB.

Finally, simulation results are presented in Fig. 6 and Fig. 7 to compare the spectrum utilization of the

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secondary system in ideal and non-ideal sensing situations according to (17). It can be seen that sensing errors considerably reduce the spectrum utilization of the entire system. For example, the results reported in Fig. 6 reveals that the spectrum utilization of the secondary system is reduced to 22% and 11% at SNR of -10 dB and -20 dB, respectively, as compared to 26% for the case of perfect sensing. Consequently, more SHs are underutilized by the secondary system due to the increase in the dropped probability. However, reducing the misdetection by increasing the SNR value to -5 dB results in only minor differences in secondary system utilization. In Fig. 7, it can be seen that reducing the false alarm probability also degrades the spectrum utilization of the secondary system as reducing false alarms increases the misdetection probability which then causes more collisions between PUs and SUs. It should be noted that the utilization shown in Fig. 6 and Fig. 7 is for the secondary system only.

V. Conclusion

In this paper, we introduce a complete mathematical analysis for an OSA system with imperfect sensing results. We analyze three performance metrics, the probability of blocked calls, the probability of dropped calls and the spectrum utilization of the secondary system, using a continuous Markov chain model. An extensive simulation is conducted to evaluate and analyze the effect of sensing errors on the considered system. Our results demonstrate the usefulness of a reliable sensing function for the effective utilization of SHs. Our mathematical modeling may be considered as a basic milestone for further analysis and investigation.

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