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Sub-banding the Secondary Users' Channel in Cognitive Radio Networks Considering Unreliable Spectrum Sensing

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Abstract One of the most efficient methods to reduce the dropping and blocking probabilities of the secondary users (SUs) in cognitive radio networks is channel sub-banding strategy. This means that when all the channels are occupied by the primary and secondary users, then the SUs' channels can be divided into two sub-bands, and two SUs can use a sub-band, simultaneously. In this paper, we propose an opportunistic spectrum sharing system in cognitive radio networks in which, the channel sub-banding strategy is implemented. Furthermore, we describe the problem of channel sub-banding considering the spectrum sensing errors such as false alarm and miss-detection events for both initial and on-going SUs' calls. Due to unreliable spectrum sensing by the SUs and subsequently possible interference with the primary users, we assume that both primary and secondary users may lose the channel due to the collision. The proposed model is analyzed by a two-dimensional Markov chain model and for performance evaluation, metrics such as blocking and dropping probabilities and channel utilization are derived. Numerical and simulation results show the accuracy of the proposed model which can be used in the evaluation of future cognitive radio networks' performance.

Keywords Opportunistic spectrum sharing · Cognitive radio · Channel sub-banding · Markov chain · Unreliable spectrum sensing

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1 Introduction

Considering the growth of telecommunication services and increasing the need for high speed data transmissions, users' demand for rare frequency spectrum resources has been increased. Conventional wireless networks use the stationary spectrum allocation methods in which spectrum allocation is done by government organizations for authorized users. Although a large part of the spectrum is currently allocated, it has been used sporadically; at the times and specific locations, these bands are not used by the relevant users. This causes a non-optimal use of the available spectrum resources and the level of spectrum efficiency has been reported very low [1,2]. Therefore, dynamic spectrum access (DSA) methods have been used to improve the efficiency of the scarce spectrum resources' usage [3,4]. Furthermore, cognitive radio networks with the ability to realize and monitor the environment for opportunistically and intelligently utilization of the spectrum holes have been proposed to solve the problem of spectral inefficiency [5,6]. A comprehensive review on the critical ongoing efforts and challenges towards the use of cognitive radio and DSA is expressed in [7].

The fundamental basis in the most of DSA methods is the opportunistic spectrum access for secondary users (SUs), in which the same spectral bands can be used by SUs without interfering with primary users (PUs) [8,9]. They can detect unused spectral bands and use them by utilizing various spectrum sensing methods. Moreover, due to the presence of PUs, these bands cannot be used by SUs, continuously. Therefore, a secondary user upon detecting a PUs in its current channel should release it, immediately. In such a case, the secondary user checks all other channels, and if there is available free channel, it switches to that channel (*spectrum hand-over*). Otherwise, the secondary user's connection is cut-off (dropped).

Some attempts addressing the spectrum sharing issue in cognitive radio networks has been recently developed in the literature. In [10] the modeling of interference based on the listen before talk (LBT) scheme in spectrum access is analyzed. Spectral efficiency can be raised by allowing the reuse of empty bands by the SUs [11], which proposed an opportunistic spectrum sharing model. Since in practical systems spectrum sensing mechanism is associated with errors, the authors have extended their model to the case of unreliable spectrum sensing in [12–14]. [14] presents and investigates an scheme based on a reconnection opportunity for the queued secondary calls in the buffer by developing a 3-D Markov process. In addition, the statistical time pattern of PUs', arrival and channel usage can affect the usability of specific frequency bands. [15] proposes a measurement-based model for statistically describing the idle and busy periods of a WLAN and [16] analyzes the effect of the arrival rate and channel holding time of PUs on the available times for cognitive radios.

In [17], authors used the channel aggregation methods in cognitive radio networks to increase the spectral efficiency of the network. By using these methods, a secondary user can gain the advantage of several separate or adjacent parts of the spectrum to be used as a channel, simultaneously. Also, two channel aggregation methods (fixed and variable) were studied in [18]. The results in [17] and [18] indicate that channel aggregation for SUs increases their throughput and makes more utilization of the spectrum. Channel reservation methods for the primary and secondary users in order to prevent call dropping was suggest in [19] and [20], while [21] introduces the usage of backup channels for the SUs.

In this paper we model a spectrum sharing system in cognitive radio networks in which sub-banding is utilized and spectrum sensing is unreliable. Unlike [19,20], and [21] that additional resources or tools such as extra bandwidth or queues (buffers) are used to reduce the dropping probability of secondary users, in this paper we introduce a new method named channel sub-banding which does not require any additional resources. The proposed method

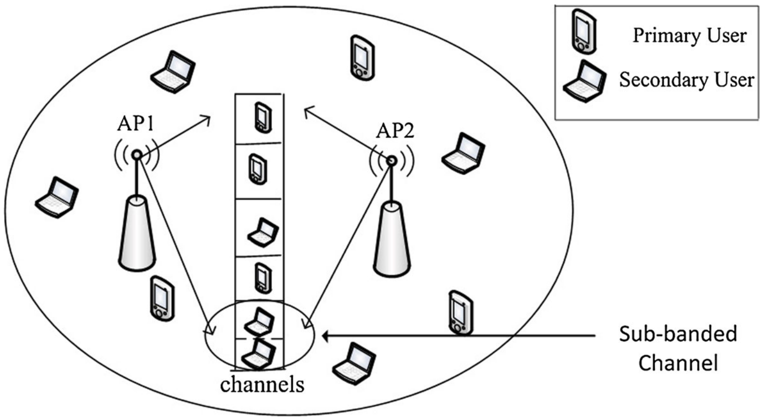

Fig. 1 General model of spectrum sharing with channel sub-banding

is such that, if all the channels are being used by the primary and/or other SUs, while a new call request of secondary user arrives, then the SUs' channels can be divided into two sub-bands, and two SUs can use a sub-band, simultaneously (i.e., both SUs coexist in the same channel, off course with half rate).

We also consider two possible cases of spectrum sensing errors by the SUs in the proposed scheme and model the unreliable spectrum sensing by considering false alarm and miss-detection errors, which may cause negative impact to the primary and secondary users' performance. We propose that both initial and ongoing SUs may make sensing errors. In these ways, we introduce different parameters, such as probabilities of the two possible cases of false alarm events, and probabilities of the two possible cases of miss-detection events, to describe these sensing errors. This brings more flexibility for performance evaluation of our model and makes it more realistic. The proposed spectrum sharing models in [11–14] were limited to the case which the number of primary and secondary users in system are equal. In contrast, our spectrum sharing model is a general one which can be easily extended to different scenarios with different number of users. For performance evaluation, we have derived metrics such as blocking probability, dropping probability as well as channel utilization, which are fully explained in the next sections.

2 Model and Assumptions

In this section, we describe a scenario of opportunistic spectrum sharing with the presence of SUs on the PUs spectrum. The considered scenario is a cognitive radio network in which the SUs opportunistically take advantages of the channels that are not used by the PUs. The cognitive radio system performance is modeled and analyzed considering the spectrum sensing errors. Also it is assumed that the channel sub-banding strategy is applied for SUs.

Consider a cognitive radio network (Fig. 1) which consists of the PUs and SUs who operate at the same spectrum bands. Spectral holes can be used by the SUs opportunistically without making any harmful interference on the PUs. The primary system access point (AP1), manages all the N channels in an area under the service. Also, accessing of the SUs to all channels is assumed to be managed by the secondary access point (AP2). Since the PUs have priority to access the spectral bands, SUs' activities do not have any impact on these users, unless the channel is not sensed correctly. For the sake of simplicity, suppose that both primary and secondary networks are infra-structured (Fig. 1). We also assume that the SUs are equipped with the channel sensors. Therefore, they are able to recognize the PUs' activities in terms of channel occupation. This means that they can distinguish whether the spectrum is used by the PUs and/or SUs [22] (by using spectrum sensing methods). When a PU appears on an ongoing SU's channel, the SU must vacate the channel and attempt to achieve other available channels. In reality, when a PU arrives and takes over a channel which is used by SU, it takes time for SU to evacuate the channel and also for spectrum handover, it takes time for an SU to move one channel to another channel, however, here we ignore these consumed times for the sake of simplicity. Note that the Fig. 1 is only a simple scenario for better insight, and it can be easily extended to other interested scenarios.

In a practical cognitive radio system, the spectrum detection mechanism, which is performed by SUs to find a free channel, may be associated with errors. In this case, some PUs' connections may be lost because of the SUs unwanted interference as a result of unreliable spectrum sensing. This happens when a primary channel is not free, but the channel sensing detects it as free by mistake. This type of failure events are known as *miss-detection* (MD) errors. This miss-detection may happen in two cases. First, when the primary channel is already occupied by a PU and then an SU sense the channel as free. The second case is when the primary channel is already occupied by an SU, and then a PU starts to use the channel. In both cases the miss-detection of the PU presence in the channel by the SU causes a severe interference between PU and SU and this may yield to dropping or blocking of PUs and/or SUs. We denote the probabilities of these miss-detection cases by p_{m1} and p_{m2}, respectively.

There are two possible scenarios that may occur due to miss-detection event. In the first scenario, both the PU and SU lose the channel at the same time, due to the heavy interference they cause on each other. In the next possible scenario, we may assume that one of the SU or PU loses the channel, first. Therefore, the other one may keep the channel for its call. In the proposed model of this paper, we assume that due to the collision between users, both users will lose the channel at the same time, because it is not simple to determine which user will keep the channel after a collision.

There is still another type of error which happens when a new SU incorrectly determines that a channel is busy, while the channel is really free. In addition, an ongoing SU may also incorrectly detect the presence of a PU on its current channel while in fact there is no PU on that channel. These types of errors are referred as *false alarm* (FA) errors. We denote the probabilities of these false alarm cases by p_{f1} and p_{f2}, respectively. Unlike miss-detection error that has a strongly negative impact on the performance of the primary system, false alarm errors do not reduce the primary system performance. However, it potentially reduces the spectral utilization of the secondary system. In this paper, system modeling and the analysis of spectrum sensing by the SUs is performed for both cases of miss-detection and both cases of false alarm errors.

Now, we explain the channel sub-banding strategy in the opportunistic spectrum sharing system of cognitive radio networks. In such a system, we assume that when all the channels are occupied by the PUs and SUs, then the SUs' channels can be divided into two sub-bands, and two SUs can use a sub-band, simultaneously, if the channel is not already occupied by the PUs. Furthermore, we describe the problem of channel sub-banding by assuming the possibility of false alarm and miss-detection errors. We also assume that both PUs and SUs lose the channel if a collision occurs, due to unreliable spectrum sensing by the SUs. By sub-banding, if there is no free channel when a new SU call request arrives, the new SU call can be served with sub-banding of other SUs' channels in the system. A new SU's call request is blocked if upon its arrival, all the channels are occupied and already sub-banded. In the following, we investigate different possible scenarios in the resource allocation process of such cognitive radio network, considering the channel sensing errors.

When a PU call request arrives into the system, it can choose any channel because of its priority over SUs. Therefore, a channel, which can be a free channel or a channel that is in-use by an SU or SUs, is randomly allocated to that PU call. Then, 8 possible scenarios may happen as follows:

1. The PU request is blocked only if upon its arrival, all the channels are already occupied by other PUs.
2. When an ongoing SU detects the presence of a PU in its current channel, the SU should release its channel to the PU because of its priority.
3. By considering the spectrum hand over, the SU switches to one of the other idle channels, if it is possible.
4. If at that time, all the channels are busy by other PUs or already sub-banded SUs, the PU achieves the channel because of its priority and the ongoing SU will be dropped.
5. If there is any other SU which is not already sub-banded, the ongoing SU switches to that channel and coexists with that SU in the same channel with a lower data rate. Obviously, by doing this scheme, the rate of data transmission will be reduced (at least by half). However, in many scenarios (such as emergency calls in disaster situations), having a lower data rate communication link between many nodes (with a low dropping rate) is much more beneficial than having a few high data rate links between some selected nodes which they are experiencing a high level of dropping rate.
6. When the PU's request arrives exactly to sub-bands which are used by two SUs (e.g. A and B), and if there are at least two other SUs (e.g. C and D) in the system that their channels are not divided to sub-bands yet, each of the two SUs (A and B) joins the other SUs' channels (C and D) and the PU occupies the initial channel.
7. In this case, if there is only one SU in the system (e.g. C), which uses non-divided channel, one of the ongoing SUs (A and B at random) coexists with the SU's channel (A), and the other SU is dropped.
8. If there is no sub-banded channel of other SUs, then the two ongoing SUs will be dropped.

When a SU's call request arrives to the system and assuming that the spectrum sensing is correct, 3 possible scenarios may happen as follows:

- The SU occupies the channel, if an idle channel is available in the system.
- If all the channels are occupied by the PUs and/ or SUs, and all the SUs' sub-bands have been occupied, then the SU's request will be blocked.
- When there is at least another SU in the system, the channel is divided to two sub-bands and the new SU coexists with ongoing SU in the same channel.

Now we describe the error scenarios and their consequences. When a SU's request arrives to the system and assuming the FA error (with the probability of p_{f1}) in spectrum sensing, the SU request is blocked. Similarly, when a SU's request arrives to the system and assuming the MD error (with the probability of p_{m1}) in spectrum sensing, the SU request is blocked. Due to simultaneous use of both PU and SU of a channel, a great interference happens, and both users lose the channel. Hence, the PU is dropped. Also, when no PUs' request arrives to the system and assuming the FA error (with the probability of p_{f2}) in spectrum sensing by an ongoing SU, the SU is dropped. On the other hand, when PU's request arrives to the system and assuming the MD error (p_{m2}) in spectrum sensing by an ongoing SU, the PU request is blocked. Due to simultaneous use of both PU and SU of a channel, a great interference causes, and both users lose the channel. Hence, the SU is dropped.

3 Performance Analysis

In this section, we develop the Markov model for dynamic spectrum access scheme by sub-banding of the SUs' channels considering unreliable spectrum sensing. We analyze the performance of both primary and secondary networks in a service area. We assume that N channels are shared between PUs and SUs so that both primary and secondary traffics are served. We also assume that all cells are statistically identical; therefore our model is analyzed in a cell. In each cell, the arrival times of PU and SU calls are independent Poisson processes with rates λ_p and λ_s, respectively. The holding times (service duration) of both PU and SU calls are assumed to be exponentially distributed with mean $1/h_p$ and $1/h_s$, respectively. The resident times of the PU and SU calls in the service area is exponentially distributed with means $1/r_p$ and $1/r_s$, respectively. We suppose that the channel holding time is equal to the minimum service duration and residence time in the given service area. Hence, channel holding time for the PU and SU calls is exponentially distributed with mean $\mu_P^{-1} = 1/(h_p + r_p)$ and $\mu_S^{-1} = 1/(h_s + r_s)$, respectively [23]. For the sake of simplicity, we assume that each user occupy only one channel per call. We define $(X_1(t), X_2(t))$ as a 2-D Markov process with state space $S = \{(k_1, k_2)|0 \leq k_1 \leq N, 0 \leq k_2 \leq 2(N - k_1)\}$ in which $X_1(t)$ and $X_2(t)$ are the numbers of PUs and SUs in the system at time t, respectively. The transition rate from state (k_1, k_2) to state (k_1', k_2') is denoted by $T_{k_1,k_2}^{k_1',k_2'}$.

Channel allocation process by the primary access point is done uniformly; i. e. a PU chooses a channel randomly with equal probability among the channels. Hence, a PU can randomly select a free channel or a channel which is occupied by an SU or SUs. The transition rate $T_{k_1,k_2}^{k_1',k_2'}$ for the Markov model can be determined as:

$$\begin{aligned}
T_{k_1,k_2}^{k_1+1,k_2} &= (1 - \bar{\delta}(k_2)p_{m2})\lambda_p 1_{\{0\leq k_1<N, 0\leq k_2<2(N-(k_1+1))\}}\\
T_{k_1,k_2}^{k_1-1,k_2} &= k_1\mu_p + p_{m1}\lambda_s 1_{\{1\leq k_1\leq N, 0\leq k_2\leq 2(N-k_1)\}}\\
T_{k_1,k_2}^{k_1,k_2+1} &= (1 - p_{f1} - \bar{\delta}(k_1)p_{m1})\lambda_s 1_{\{0\leq k_1\leq N-1, 0\leq k_2\leq 2(N-k_1)-1\}}\\
T_{k_1,k_2}^{k_1,k_2-1} &= k_2\mu_s 1_{\{0\leq k_1\leq N-1, 1\leq k_2\leq 2(N-k_1)\}} + (p_{m2}\lambda_p + p_{f2}k_2\mu_s)1_{\{k_2=2(N-k_1)\}}\\
T_{k_1,k_2}^{k_1+1,k_2-1} &= (1 - p_{f2} - p_{m2})\lambda_p 1_{\{0\leq k_1<N, k_2=2(N-k_1)-1\}}\\
T_{k_1,k_2}^{k_1+1,k_2-2} &= (1 - p_{f2} - p_{m2})\lambda_p 1_{\{0\leq k_1<N, k_2=2(N-k_1)\}}
\end{aligned} \tag{1}$$

Spectrum sensing errors can cause different channel occupation status and also can lead to the different transitions in system. Figure 2 illustrates the diagram of the system with all the possible transitions and corresponding transition rates . The Eq. (1) formulates the transition rates of Fig. 2. Let, $1_{\{x\}}$ denote the indicator function in which $1_{\{x\}} = 1$ if x is true and is 0 otherwise.

The transition from (k_1, k_2) to $(k_1 + 1, k_2)$ is denoted by $T_{k_1,k_2}^{k_1+1,k_2}$ which shows that a PU arrives to the system while the number of SUs does not change. The rate of this transition is $(1 - \bar{\delta}(k_2)p_{m2})\lambda_p$ in which p_{m2} occurs when there is at least one SU in system. Let, $\bar{\delta}(x) = 0$ for every $x = 0, x \in \{k_1, k_2\}$ and $\bar{\delta}(x) = 1$ in other cases. Hence, $\bar{\delta}(k_2) = 0$

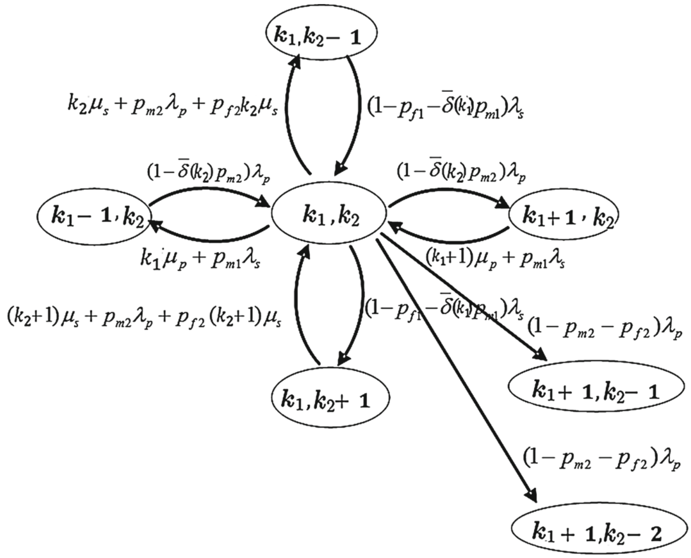

Fig. 2 Transition diagram for channel sub-banding with unreliable spectrum sensing

if $k_2 = 0$ i.e. there is no SU in the system. On the other hand, in this case there should be at least a free channel (i.e. $0 \le k_1 < N$) which can be occupied by the new PU ($1_{\{0\le k_1<N, 0\le k_2<2(N-(k_1+1))\}}$).

A forced PU disruption depends on the probability of miss-detection (p_{m1}). Transition from state (k_1, k_2) to $(k_1 - 1, k_2)$ represent the state in which while the number of SUs is not changed, a PU releases the channel either when its service time has been completed or a miss-detection error occurs by a new SU. This transition is denoted by $T_{k_1,k_2}^{k_1-1,k_2}$ and occurs with the rate of $k_1\mu_p + p_{m1}\lambda_s$. The term $k_1\mu_p$ is because of the PUs' completion service and the term $p_{m1}\lambda_s$ is because of the miss-detection error by the SUs to the PUs. In this case, there should be at least a PU in system (i.e. $1 \le k_1 \le N$) and the number of SUs changes based on the number of PUs in the system.

Similarly, the transition from (k_1, k_2) to $(k_1, k_2 + 1)$ is denoted by $T_{k_1,k_2}^{k_1,k_2+1}$ which shows that an SU arrives to the system while the number of PUs does not change. Due to the impact of errors, this state occurs with the rate of $(1 - p_{f1} - \bar{\delta}(k_1)p_{m1})\lambda_s$. In order to have a perfect transition, the errors with the probabilities of the p_{f1} and p_{m1} should not be occurred. Note that $k_1 = 0$, i.e. when there is no PU in the system, therefore $p_{m1} = 0$. In other words, the p_{m1} occurs when there is at least a PU in the system.

An SU releases the channel when either its service completes ($k_2\mu_s$) or one of the SE occurs ($p_{m2}\lambda_p + p_{f2}k_2\mu_s$). In this case, there should be at least one SU in the system. This transition rate is denoted by $T_{k_1,k_2}^{k_1,k_2-1}$ and can be concluded as follow:

- The service time of the SU has been completed ($k_2\mu_s$).
- An ongoing SU can not determine the presence of a new PU on its current channel ($p_{m2}\lambda_p$).
- An ongoing SU incorrectly detects the presence of the new PU on its current channel while there is no PU on it ($p_{f2}k_2\mu_s$).

A forced SU disconnection depends on the users in system and the channels' status that are not used by them. Two transitions rates $T_{k_1,k_2}^{k_1+1,k_2-1}$ and $T_{k_1,k_2}^{k_1+1,k_2-2}$ represent the states in which an SU and two SUs' calls are dropped in the system, respectively, given that the second case of errors does not occur. An SU will be blocked when either all the channels are occupied by the PUs and/or SUs and there is no available sub-band of other SUs in system, or a FA error occurs by a new SU. Hence, an SU can use a channel when none of the false alarm and miss-detection errors occurred by a new SU.

Let $I_{(k_1,k_2)}$ define a function in which $I_{(k_1,k_2)} = 1$ if $2k_1 + k_2 \leq 2N$ and $I_{(k_1,k_2)} = 0$ in other cases. We denote $\pi(k_1, k_2)$ as the steady state probability in which the system is in the state (k_1, k_2). The steady state probabilities are the probabilities of stationary states at time t, hence the sum of transition rates that originate from the state $X_i(t) \in S_{|i=1,2}$ are equal to the sum of transition rates that terminate to the state $X_i(t)$. Then, the balanced state equation is expressed as follows:

$$\begin{aligned}
&(T_{k_1,k_2}^{k_1+1,k_2} + T_{k_1,k_2}^{k_1-1,k_2} + T_{k_1,k_2}^{k_1+1,k_2-1} + T_{k_1,k_2}^{k_1+1,k_2-2} + T_{k_1,k_2}^{k_1,k_2+1} + T_{k_1,k_2}^{k_1,k_2-1}) I_{(k_1,k_2)}\, \pi(k_1, k_2) \\
&= T_{k_1+1,k_2}^{k_1,k_2} I_{(k_1+1,k_2)} \pi(k_1 + 1, k_2) + T_{k_1-1,k_2}^{k_1,k_2} I_{(k_1-1,k_2)} \pi(k_1 - 1, k_2) \\
&+ T_{k_1,k_2+1}^{k_1,k_2} I_{(k_1,k_2+1)} \pi(k_1, k_2 + 1) + T_{k_1,k_2-1}^{k_1,k_2} I_{(k_1,k_2-1)} \pi(k_1, k_2 - 1) \qquad (2)
\end{aligned}$$

and also we have:

$$\sum_{k_2=0}^{2N} \sum_{k_1=0}^{N} \pi(k_1, k_2) I_{(k_1,k_2)} = 1 \qquad (3)$$

After computing the steady state probabilities which are mentioned above, we can determine different required metrics which is explained in the next section.

4 Performance Metrics

In this section we describe various measures of interest, such as Channel Utilization as well as Blocking and Dropping Probabilities for both primary and secondary users.

4.1 Blocking Probability

– Blocking probability of SUs

The blocking of the SUs happens when either an error (FA with the probability of p_{f1} or MD with the probability of p_{m1}) occurs or an SU arrives in the system while all the channels are occupied by PUs and/or SUs. At that time, no sub-band is available for a new SU call request, i.e. all channels of SUs have already divided and occupied. Blocking Probability of the SUs is denoted by PB_{SU} that is given by:

$$PB_{SU} = \sum_{k_1=0}^{N} \pi(k_1, 2(N - k_1)) \qquad (4)$$

– Blocking Probability of PUs

A PU call request is blocked when upon the arrival of a primary call request either an MD error (with the probability of p_{m2}) occurs or all the channels have been occupied by PUs. At that time, no free channel is available for a new PU call request. Blocking Probability of the PUs is denoted by PB_{PU}. Note that it does not depend on the channel sub-banding strategy by the SUs and it is obtained as:

$$PB_{PU} = \pi(k_1 = N, k_2 = 0) \qquad (5)$$

4.2 Dropping Probability

– Dropping Probability of SUs

An SU and/or SUs will be dropped when either an error (MD with the probability of p_{m2} or FA with the probability of p_{f2}) occurs or all the channels are busy by PUs and/or SUs and also there is no available channel for an ongoing SU or SUs in order to switch to. Note that in this case all channels of SUs have already divided and occupied. Note also that in such a case, there should be at least one SU in the system. Dropping Probability of the SUs is denoted by PD_{SU} and can be written as follows:

$$PD_{SU} = \sum_{k_2=1}^{2N}\sum_{k_1=0}^{N-1}(T_{k_1,k_2}^{k_1+1,k_2-1}\pi(k_1,k_2) + T_{k_1,k_2}^{k_1+1,k_2-2}\pi(k_1,k_2))I_{(k_1,k_2)}$$
$$= \sum_{k_1=0}^{N-1}\pi(k_1, 2(N-k_1)-1) + \pi(k_1, 2(N-k_1)) \tag{6}$$

– Dropping Probability of PUs

A primary call request will be dropped when upon the arrival of an SU call request, an MD error (with the probability of p_{m1}) occurs by a new SU. Whereby both PU and SU lose the channel and the ongoing PU connection is interrupted from system. Note that in such a case, at least one PU should be available in the system. Dropping Probability of the PUs is denoted by PD_{PU} and can be written as follows:

$$PD_{PU} = \sum_{k_2=0}^{2N-2}\sum_{k_1=1}^{N}(T_{k_1,k_2}^{k_1-1,k_2}\pi(k_1,k_2))I_{(k_1,k_2)} \tag{7}$$

4.3 Channel Utilization

The ratio of the mean number of occupied channels (i. e. the total carried traffic by both PUs and SUs which is supported in a given service area) to the number of all channels is defined as Channel Utilization. It is denoted by η and can be written as follows:

$$\eta = \frac{1}{N}\sum_{k_1=0}^{N}\sum_{k_2=0}^{N-k_1}((k_1+k_2)\pi(k_1,k_2))I_{(k_1,k_2)} \tag{8}$$

In calculating this utilization, it is assumed that one channel is busy, when a channel is occupied by two SUs.

5 Numerical and Simulation Results

In this section, we present the numerical and simulation results to obtain the performance of the proposed method. Here, we show the impact of channel sub-banding as well as unreliable spectrum sensing on desired metrics. To obtain these results, we consider a cellular system in which each cell has 10 channels available. We assume that the arrivals of both PU and SU calls are independent Poisson process with parameter $\lambda_p = \lambda_s = 1$ *call/hour*, and the call time of users is also assume to be exponentially distributed with the mean of 30 sec. The number of PUs per each cell is further assumed to be constant and it is equal to 500, while

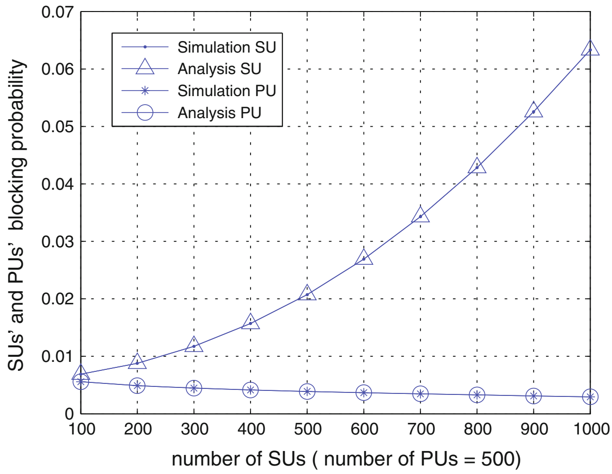

Fig. 3 Validation of PUs' and SUs' call blocking probabilities $p_f = p_m = 0.05$

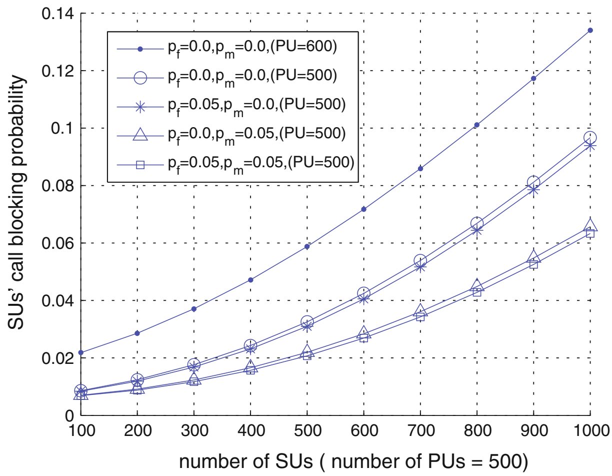

Fig. 4 SUs' call blocking probability

the number of SUs changes to study the effect of users' number on the PUs' performance. Let $p_{f1} = p_{f2} = p_f$ and $p_{m1} = p_{m2} = p_m$, we study the impact of unreliable spectrum sensing on the performance of system by setting different values of errors' parameters. Furthermore, we compare the system performance with the reliable spectrum sensing by choosing $p_f = p_m = 0$.

First, we validate the analysis of blocking probabilities for both PUs and SUs, by comparing the simulation and analytical results and with one set of the parameters ($p_f = p_m = 0.05$) as indicated in Fig. 3. This figure shows an excellent compliance between simulation and analysis of the proposed schemes for both PUs and SUs and for different SU numbers. Notice that sub-banding has no effect on PUs' call blocking probability.

Figure 4 shows the blocking probability of SUs as a function of the number of SUs. As you can see from the figure, the SUs' blocking probability increases as the traffic increases, as we expected. Also, the figure shows the impact of both FA and MD probabilities on the

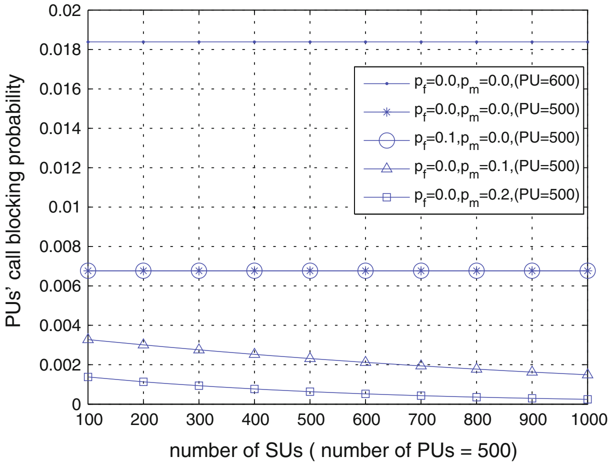

Fig. 5 PUs' call blocking probability

SUs' blocking probability. When p_f or p_m increases, the probability of blocking decreases, slightly. This can be explained as follows. When the FA error occurs, then the channels remain empty and potentially will be used by other new users. On the other hand, a MD error directly affects on releasing a channel which is currently used by a PU. This leads to more opportunities for new SUs to arrive into the system. It is clear that the MD error reduces the performance of the system. As shown in figure, also changing the number of PUs affects on the SUs' blocking probability. Reducing the number of PUs reduces the SUs' blocking probability and contrary. The reason is they have to compete with more users to accessing the fix number of channels. It is clear that all the SUs' activities are affected by the PUs' activities and PUs' performance to access the channel.

Figure 5 shows how the blocking probability of PUs changes with increasing the SUs' number. We observe that increasing the SUs' population and also changing the false alarm probability (p_f) have no effect on PUs' call blocking probability. This shows that in an ideal cognitive radio system, the SUs' activities have no effect on PUs' performance. On the other hand, we can see that increasing the p_m decreases the PUs' blocking probability. The reason is that the increase of p_m lead to the reduction of channels' activity and subsequently, additional opportunities is caused to arrival of a new PU. It is obvious that the blocking probability of SUs increase as the number of PUs increase. And increasing the SUs' population also have no effect on PUs' blocking probability, as should be expected.

Figure 6 shows the SUs' dropping probability in terms of increasing the SUs' population. It is obvious that for a fixed number of PUs, whatever the number of SUs who occupy the channels be, some of their connections will be disrupted, forcibly. It is due to the fact that with the arrival of PUs to accessing the SUs' channel, there are a fewer sub-bands from other SUs to switch to it. When $p_f = 0$ and $p_m = 0$, i.e. when no error occurs, the dropping probability of these users is more in comparison with the state which error occurs. Furthermore, the miss-detection error has more impact on dropping of these users and with increasing it, the dropping probability decreases. It can be explain as follows. A miss-detection error directly affects on releasing a channel which is currently used by a PU and the PU loses its channel due to the collision with the SU. In such a case, a channel will be empty in the system. This causes that with the arrival of other PUs to accessing the SUs' channel, there are more empty

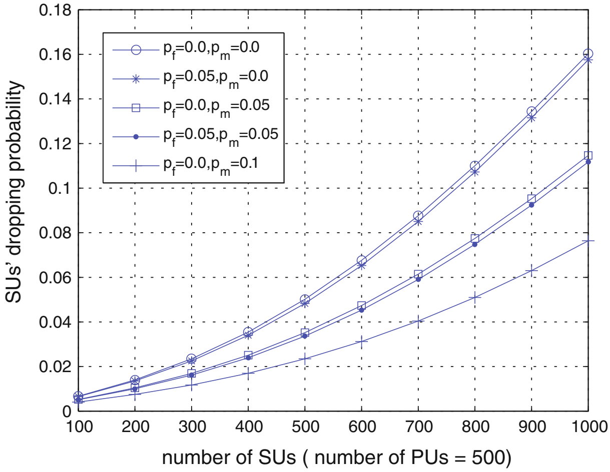

Fig. 6 SUs' call dropping probability

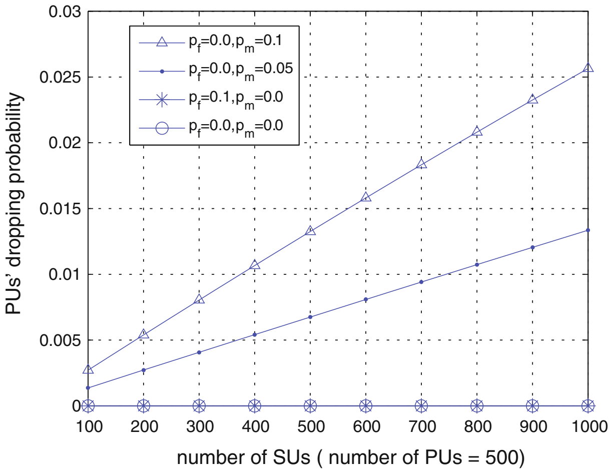

Fig. 7 PUs' call dropping probability

channels that the ongoing SUs switch to it. Thus, the more p_m probability of miss-detection error, the more PUs loses the channels and the less dropping probability of SUs. But, it causes more declines in the performance of primary system and has undesired effects on it. On the other hand, when the FA error occurs, then the channels remain empty and just using a one free channel is wasted. At that time with the arrival of a PU on the SUs' channel, the ongoing SU has an opportunity that switch to it. The FA error has less effect because, it only occurs when there is at least a free channel in system.

Figure 7 shows the dropping probability of PUs as a function of SUs' population. As we expected, the PUs' dropping probability increases as the traffic increases. When $p_f = 0$ and $p_m = 0$, i.e. when no error occurs, the dropping probability of these users is equal to zero. We also observe that the increase of p_f has no effect on PUs' dropping probability. On the other hand, a MD error causes the releasing of a working channel, and leads to

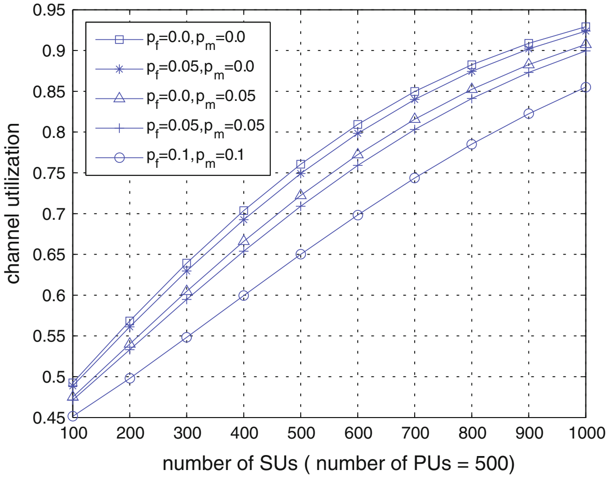

Fig. 8 Channel utilization

additional opportunity for a new arrival of users. By increasing the number of SUs, it is more likely that more number of SUs experience error. Therefore, the more p_m, the more dropping probability of the PUs and this has a negative effect on the primary systems' performance.

In Fig. 8 we observe that the channel utilization decreases with increasing the number of SUs and the probabilities of spectrum sensing errors. Furthermore, channel utilization is higher in the case of $P_f = 0.05$ and $P_m = 0$ than $P_f = 0$ and $P_m = 0.05$. Because, a false alarm error only loses a free channel, whereas a miss-detection error not only loses a free channel, but also causes the channel changes from busy to vacant status. Therefore, a miss-detection error degrades the performance of system more than a false alarm error.

6 Conclusion

In this paper, we proposed an opportunistic spectrum sharing system in a cognitive radio network. The network was included two types of primary and secondary users which share the number of channels under a given service area. Modeling was done under the sub-banding strategy considering the spectrum sensing errors. The sub-banding is such that, if all the channels are occupied by the primary and/ or secondary users, then the SUs' channels can divided into two sub-bands and two SUs can coexist in the same band, simultaneously. Unreliable spectrum sensing including false alarm and miss-detection events, was considered not only for a new secondary user but also for an ongoing one. It was assumed that both primary and secondary users lose the channel due to the collision. Analysis was performed by using Markov model. For performance evaluation, we have derived metrics such as, blocking and dropping probabilities, as well as channel utilization. The results show that the opportunistic spectrum sharing under the sub-banding strategy can improve the system performance and spectral efficiency even under the unreliable spectrum sensing. The proposed method can be easily generalized to the case of channel sub-banding to N channels or be used to evaluate the performance of upcoming opportunistic spectrum sharing networks.

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