# Analysis of Guard-band-aware Spectrum Bonding and Aggregation in Multi-Channel Access Cognitive Radio Networks

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***Abstract*—Adjacent channel interference (ACI) is often not considered when spectrum sharing schemes are designed for cognitive radio networks (CRNs). In practice, it is necessary to avoid interference by deploying guard bands between two distinct receptions. However, using guard bands typically reduces spectrum efficiency. In this work, we study the impact of guard bands on spectrum efficiency under different spectrum sharing schemes. Specifically, we model cognitive radio network as a continuous-time Markov process. We derive blocking probability, forced termination probability, spectrum efficiency and average number of guard bands using our Markov model. Using these metrics, we then study and analyze the impact of using guard bands on the performance of cognitive radio networks. We show that taking guard bands into consideration is critical as disregarding this realistic issue results in inaccurate conclusions and outcomes.**

***Index Terms*—Cognitive Radio Networks; Performance modeling and analysis; guard-band; continuous time Markov process**

## I. Introduction

FCC and other regulatory bodies conducted studies on the causes of spectrum scarcity at a given time in any location. The results of the studies indicate that less than 10 percent of the spectrum is utilized [1, 2]. Therefore, FCC was convinced that the use of cognitive radio, which provides the capability of opportunistic spectrum access, is necessary in order to improve spectrum utilization. Consequently, a pervasive research has been done on cognitive radio networks recently. Opportunistic spectrum access should guarantee that cognitive radio users do not affect primary radio users. Cognitive radio users (CU) may coexist with primary radio users (PU) without making harmful interference with them. CUs have to vacate a channel if it is reclaimed by a PU. An important objective in this domain is how to model, characterize and analyze the system performance considering practical constraints.

### A. Motivation

Many works have been done in the literature, proposing models for performance evaluation of CRNs (e.g., [3–10]). In most of these works, adjacent-channel interference (ACI) is often not considered, hence they require ideal transmission filters while, in practice, signal filtering causes spectrum spill-over due to non-ideal filters. In order to protect adjacent PU and CU transmissions, there should be a frequency separation. Such separation is referred to as a guard band. However, using guard bands restricts effective spectrum utilization. CUs should consider guard band issue when they choose channels for their transmission. However, if two contiguous channels belong to the same CU there is no need for a guard band between them. Set of contiguous channels assigned to the same CU is called a frequency block.

We note that ACI impact in CRNs was previously studied in [4]. Specifically, a centralized solution for adaptive guard-band setting was proposed. Their solution uses a dynamic guard-band configuration to minimize ACI, requiring a central server for frequency planning. In [4], the authors did not consider channel aggregation and did not deal with the channel assignment problem.

### B. Contributions

In this work, we model a multichannel access cognitive radio as a continuous time Markov process under the realistic assumption of non-ideal filters (i.e., guard bands are needed). We then use our model to derive blocking and forced termination probability of the CUs as well as spectrum efficiency and average number of guard bands needed under three channel assignment algorithms. We consider an FDM-based cognitive radio network in which it does not allow two neighboring CU transmissions to share the same guard band.

Note that despite our model simplicity, it can be easily used to derive many important performance metrics of the network. Additionally, it provides accurate results which significantly helps in analysis of the cognitive network.

### C. Organization

The rest of the paper is organized as follows. In Section II, we describe the system model considering constraints imposed by adjacent channel interference. Section III introduces three guard-band-aware channel assignment schemes which will be used for analysis. In Section IV, we describe our continuous time Markov process model and derive network performance metrics. Analytic results and analysis are presented in Section V. Finally, Section VI gives the concluding remarks.

## II. System Model

We consider a cognitive radio multi-channel network which contains a set of $n$ contiguous non-overlapping spectrum bands. These bands are used by two types of geographically coexisting users; Primary Users (PUs) who have exclusive rights to access the spectrum bands, and

Cognitive Users (CUs) who are allowed to use the bands as long as they do not cause interference to PUs.

CUs are only allowed to use a band only when there is no PU transmission operating over that band because PUs have a strict priority to use the spectrum bands. We assume that CUs are always aware of the presence of PUs and that, as soon as a PU reclaims its band, CUs immediately vacate the band and switch to another idle band, if any exists. However, we know that there is a delay associated with spectrum handoff and spectrum sensing but since these delays are bounded [11, 12] and they do not impact the performance metrics that we study in this paper, we can ignore these delays.

The multichannel access capability can be implemented using frequency division multiplexing (FDM), or discontinuous orthogonal frequency division multiplexing (D-OFDM) [3, 13, 14]. In this work, we consider an FDM-based CRN in which each CU is equipped with $m$ half-duplex radio transceivers, which enables a CU transmission to be fulfilled over, at most, $m$ bands simultaneously. A CU transmission may be carried over multiple contiguous (i.e., bonded) or noncontiguous (i.e., aggregated) available bands, depending on the spectrum opportunities.

We assume that CUs use tunable raised-cosine pulse filters. The number of bands belonging to a frequency block and roll-off factor of the filter $\beta$ determines the number of guard bands required for that frequency block. $\beta$ is a measure for the excess bandwidth of the filter due to a spill-over. Formally, a CU transmission that uses a frequency block of $k$ adjacent channels has an excess bandwidth on each side of the frequency block of $\Delta f = kW\frac{\beta}{2}$. In this case, ACI can be alleviated using only one guard band of bandwidth $W$ on each side of the frequency block.That is, $\Delta f \leq W$, implying $k \leq \frac{2}{\beta}$. Considering practical values for $k$, $\beta$, and $W$, the above condition often holds. For example, with $\beta = 0.1$ and $W = 3$MHz, $k \leq 20$ channels (i.e., a data rate of up to 60 Mbps). Accordingly, it is reasonable to assume that a guard band of bandwidth $W$ on each side of a frequency block is sufficient to protect the reception over that block and avoid harmful interference to neighboring transmissions. Therefore, two guard bands separate two frequency blocks assigned to neighboring distinct CU transmissions. This means that if a guard band is reserved for a CU transmission, it cannot be reused (shared) by another CU transmission [15]. However, we consider only one guard band between a CU transmission and a PU transmission.

## III. Channel Selection Schemes

The required number of guard bands depends on how bands are allocated to CUs transmissions. Allocation of the bands is determined by the schannel assignment scheme used by the CUs. Therefore, we need to consider various channel selection algorithms when we study the impact of guard-bands in CRNs.

- **Greedy Algorithm**
  Simplicity and low overhead of this algorithm makes it an attractive for use in multichannel systems [5, 16, 17]. Upon arrival of an incoming CU, it chooses the first $n$ available bands as it scans through the bands. Note that the CUs choose the frequency blocks considering the required guard bands. This approach is simple and quick as it does not require to sense all of the channels.
- **Reducing the Number of Guard Bands - Min GB (Local)**
  We propose an assignment scheme which aims to minimize the number of guard bands, thus reducing the number of required guard bands which results in higher spectrum efficiency as more bands can be used for CU transmissions. When a CU arrives, it chooses a set of channels that causes the least number of guard bands to be added to the existing ones.
- **Minimizing the Number of Guard Bands - Min GB (Global)**
  Another approach to channel assignment is to make all the CUs minimize the total number of frequency blocks when a new CU arrives. This algorithm is different from the previous one as in this algorithm, all the CUs enter the process of choosing a set of channels and some type of coordination is needed to fulfill this. In the previous algorithm, which is called Min GB(Local), when a CU arrives, other CUs continue their transmission on their current channels. Thus, it is possible that the algorithm does not always provide optimal solution while MinGB(Global) always chooses an optimal solution. One may argue that why we need other algorithms if MinGB(Global) is optimal. The reason is that the problem of finding an optimal solution to minimize the number of guard bands is NP-hard, hence MinGB(Global) is not an efficient algorithm. Moreover, MinGB(Global) requires a central coordinator which makes even solving the problem more sophisticated. We want to emphasize that we only propose this algorithm for comparison purposes.

## IV. Modelling and Characterization

We model the channel selection process as a continuous-time Markov process, which is defined by its states and transition rates. Here, we need to define the states and state transition rates. Bands are used by both PUs and CUs. Therefore, we define each state as an $n$-tuple, $(a_1, \cdots, a_n)$ in which $a_i$, for $i = 1, \cdots, n$, indicates that band $i$ is assigned to CU numbered $a_i$, if $a_i > 0$; or, if $a_j$ is equal to -1, it indicates that band $j$ is occupied by a PU. If $a_j$ is equal to 0, it means that the corresponding band is not assigned for any transmissions (i.e., the band is either idle or used as guard). Note that if $a_i = a_j > 0$, bands $i$ and $j$ are assigned to the same CU numbered $a_i$. It is important to keep track of the bands used by each CU since we need to know which bands become idle when a CU transmission is over or which CUs are affected when a PU reclaims a band.

We try to reduce the number of states in our model since the complexity of solving Markov process balance equations depends directly on the number of states. Hence, in order to reduce the number of states in our model, we add other constraints without loss of generality. We require that, in any state $(a_1, \cdots, a_n)$, if

$$0 < a_i < a_j$$

for some $i, j = 1, \cdots, n$, then

$$\min\{k|a_k = a_i, k = 1, \cdots, n\} < \min\{k|a_k = a_j, k = 1, \cdots, n\}$$

and

$$\min\{a_k|a_k > 0, k = 1, \cdots, n\} = 1$$

We know that $a_i$ takes only values between $-1$ and $n/3+1$ (i.e., $-1 \geq a_i \geq n/3+1$). Thus, the number of states is at most $(n/3+3)^n$. Note that, some of the states we count are invalid state as they do not satisfy the above constraints.

We model arrivals and departure of CUs and PUs both as Poisson processes with arrival rates $\lambda_c$ and $\lambda_p$, respectively, and the service times are exponentially distributed with rates $\mu_c$ and $\mu_p$, respectively. Arrival or departure of a PU or a CU create a possible state transition. In order to compute transition rates we need to look at four cases/events under which a state transition occurs; thus, we only have to consider these four cases to compute the transition rate matrix $\mathbf{Q}$. Let $s = (a_1, \cdots, a_n)$ denote the current system state in all the following cases.

1) First, consider that a CU arrives to the system and selects at most $n$ spectrum bands. The next state depends on the bands selected for CU transmission and is determined by the channel selection algorithm used by the CU. If there are at least three contiguous idle bands the transition rate from current state $s$ to the new state $s'$ is $\lambda_c$. Note that the algorithms we use in this work are deterministic and result in one possible new state. Moreover, incoming CU will be blocked and denied access to the spectrum bands if the current state $s$ does not contain at least three contiguous idle bands.
2) Second, consider that a CU leaves spectrum band $i$. In this case, the bands used for that CU transmission become idle and the transition rate from current state $s$ to the new state $s'$ is $\mu_c$.
3) Third, when a PU leaves band $i$, the next state is $s' = (a_1, \cdots, a_i', \cdots, a_n)$, where $a_i' = 0$ and $a_i = -1$. Assuming that the number of occupied bands by PUs $\alpha$, which means that the number of succeeding states is also $\alpha$, the transition rate from $s$ to $s'$ is then $\mu_p/\alpha$, where $\alpha$ can be different for different states, and it can be calculated via $\alpha = \sum_{l=1,a_l=-1}^{n} 1$.
4) Fourth, consider that a PU arrives to spectrum band $i$. Note that PUs operate on a predefined band hence they do not select any band upon their arrivals. In this case, affected CU transmission has to find new idle bands to proceed. Thus, the next state is determined by the channel selection algorithm used and since, as mentioned earlier, the algorithms used in this work are deterministic, there is only one possible next state. Hence, the transition rate to the new state $s'$ is $\lambda_p$. Note that if the all transmissions belonging to same CU are affected and that CU does not find any bands to proceed its transmission then that CU transmission is terminated.

Note, only in case 1, a CU might be totally blocked since CU arrival only takes place under that case. Also, a CU might be forced to terminate its transmission under case 4 since an ongoing CU transmission can only be affected when a PU reclaims its band.

Thus far, we computed the transition rates, and we were able to determine the transition rate matrix $\mathbf{Q}$. One can solve the following system of equations:

$$\boldsymbol{\pi}.\mathbf{Q} = 0 \textit{ and } \sum_{s \in S} \pi_s = 1 \tag{1}$$

where $S$ is the set of possible states, $\boldsymbol{\pi}$ is the stationary probability matrix and $\pi_s$ is the stationary probability of state $s$.

Now, the blocking probability $P_b$ of a CU can be defined as

$$P_b = \sum_{s \in B} \frac{\lambda_c \pi_s}{\sum_{s \in S, s \neq s'} \gamma_{s'}^{s}} \tag{2}$$

where $\gamma_s^{s'}$ is the transition rate from state $s$ to $s'$ and $B$ is the set of states in which blocking occurs when a new CU arrives to the system, and is defined as

$$B = \{s \in S | N_a(s) = 0\}$$

where $N_a(s)$ is the number of available bands (i.e., number of available bands excluding guard bands) in state $s$. The number of available bands in state $s = (a_1, \cdots, a_n)$ can be written as $N_a(s) = \sum_{i=1}^{n} \Pi_{j=i-1}^{i+1} I(a_j)$ where $I(a)$ is an indicator function defined as

$$I(a) = \begin{cases} 1 & \text{if } a = 0 \\ 0 & \text{if } a \neq 0 \end{cases}$$

The forced termination probability $P_f$ of a CU can be defined as

$$P_f = \frac{\sum_{(s,s') \in T} \pi_s \gamma_s^{s'}}{(1 - P_b)\lambda_c} \tag{3}$$

where $\gamma_s^{s'}$ is the transition rate from state $s$ to $s'$, $P_b$ is the blocking probability as defined above and $T$ is the set of pairs of states in which a CU is forced to terminate all of its transmissions when transitioning from $s$ to $s'$, and can be defined as

$$T = \{(s, s') | N_a(s') = 0, N_{CU}(s) = N_{CU}(s') + 1, N_{PU}(s) = N_{PU}(s') - 1\}$$

where $N_a(s')$, as defined earlier, denotes the number of available bands to CU in state $s'$, $N_{CU}(s)$ and $N_{PU}(s)$ denote the number of cognitive users and primary users in state $s$, respectively. The number of primary users in state $s = (a_1, \cdots, a_m)$ can be defined as $N_{PU}(s) =$

$\sum_{i=1,a_i=-1}^{m} 1$. The number of cognitive users in state $s = (a_1, \cdots, a_n)$ can be defined as $N_{CU}(s) = \max_i\{a_i\}$, for $1 \leq i \leq n$.

In addition to forced termination and blocking probabilities, we can derive spectrum efficiency and average number of guard bands. Spectrum efficiency, $\Xi$, is the ratio of number of bands used for either a PU or a CU transmission to total number of bands. We formally define spectrum efficiency as

$$\Xi = \sum_{s \in S} \pi_s \xi_s \tag{4}$$

where $\xi_s$ is the number of bands used for a PU or CU transmission in state $s = (a_1, \cdots, a_m)$ and is defined as $\xi_s = \sum_{i=1,a_i \neq 0} 1$. Similarly, we can define the average number of guard bands, $\chi$,as

$$\chi = \sum_{s \in S} \pi_s \kappa_s \tag{5}$$

where $\kappa_s$ is the number of guard bands in state $s = (a_1, \cdots, a_n)$ and is defined as

$$\kappa_s = \sum_{\substack{i=1 \\ (a_{i-1} \neq 0 \bigvee a_{i+1} \neq 0) \\ a_i = 0}}^{n} 1$$

We need to define $a_0$ and $a_{n+1}$ to be equal to zero in order to avoid out of range indices.

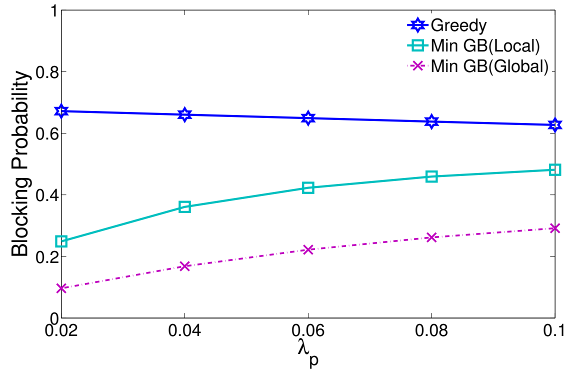
## V. Analytic Results and Analysis

In this section, we analyze the performance of multichannel cognitive radio spectrum access system under various guard band aware channel selection schemes. We study the impact of guard bands on CUs' forced termination and blocking probabilities. We use MATLAB to generate transition rate matrix $\mathbf{Q}$ first, then solve Eq. 1, and finally calculate blocking and forced termination probabilities for the CUs as well as spectrum efficiency and average number of guard bands in a multichannel access system where primary and cognitive users arrive to the system according to Poisson process with arrival rates $\lambda_p$ and $\lambda_c$, respectively.

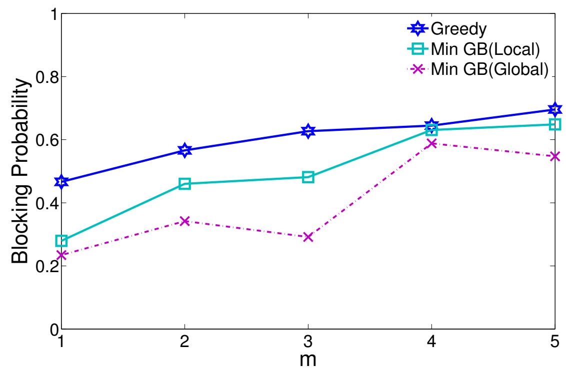
### *A. Impact of Guard Band Awareness on Blocking Probability*

Fig.1(a) depicts the derived blocking probability of CUs as a function of the primary user arrival rate $\lambda_p$ and Fig.1(b) depicts blocking probability as a function of the number of radios of each cognitive user $m$ under three different channel assignment schemes. The blocking probability is defined as the probability that a cognitive user, attempting to access the multichannel system, is rejected accessing to the system due to not finding any available band.

First, observe that the blocking probability of cognitive users increases with the primary user arrival rate. That is, as the rate of primary users increases, the network becomes more and more loaded, resulting in higher blocking probability. Second, as the number of radios per CU increases, the number of occupied bands by CUs increases,




(a) $P_b$ vs. $\lambda_p$




(b) $P_b$ vs. $m$

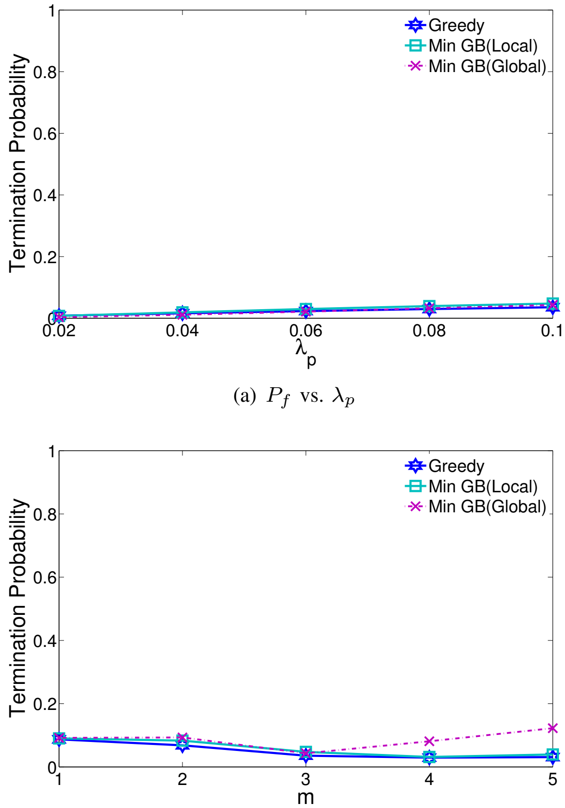
Fig. 1. Blocking probability as a function of (a) the primary arrival rate $\lambda_p$ (b) the number of a CU radios $m$, under three different channel assignment schemes ($\mu_p = 10$, $\lambda_c = 1$, $\mu_c = 10$, $n = 10$)

resulting in higher blocking probability as expected. This trend of performance behavior is expected, as having less channels to choose from, decreases the chances of cognitive users finding available bands, which explains the increase in the blocking probability of cognitive users. Third, as expected, the blocking probability is smaller when the channel assignment scheme tries to minimize the number of guard bands, resulting in leaving more available channels for the newly incoming CUs, thus having smaller blocking probabilities.

### *B. Impact of Guard Band Awareness on Termination Probability*

We study the impact of guard bands on forced termination probability of cognitive users, defined as the probability that a cognitive user, already accessing and using a set of channels is affected by a PU that has returned, is forced to stop transmission as a result of not finding an available band. Fig.2(a) plots the derived forced termination probability of cognitive users as a function of the primary user arrival rate $\lambda_p$ and Fig.2(b) depicts the forced termination probability as a function of the number of radios for each cognitive user $m$ under three different channel assignment schemes.

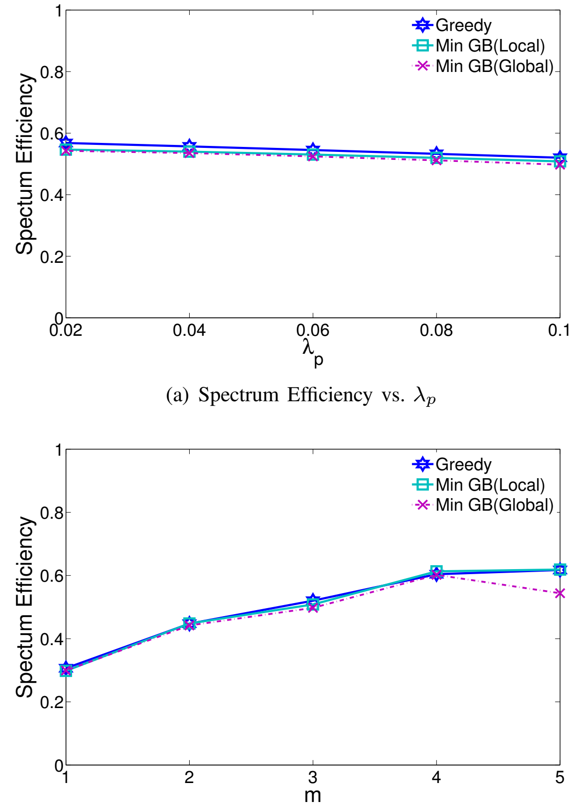
First, observe that the termination probability increases slowly as the primary user arrival rate increases. That




(a) $P_f$ vs. $\lambda_p$

(b) $P_f$ vs. $m$

Fig. 2. Forced termination probability as a function of (a) the primary arrival rate $\lambda_p$ (b) the number of radios $m$, under three different channel assignment schemes ($\mu_p = 10$, $\lambda_c = 1$, $\mu_c = 10$, $n = 10$)




(a) Spectrum Efficiency vs. $\lambda_p$

(b) Spectrum Efficiency vs. $m$

Fig. 3. Spectrum Efficiency as a function of (a) the primary arrival rate $\lambda_p$ (b) the number of radios $m$, under three different channel assignment schemes ($\mu_p = 10$, $\lambda_c = 1$, $\mu_c = 10$, $n = 10$ )

is, as the rate of primary users increases, the chance of a CU be affected by a PU activity increases, resulting in slightly higher forced termination probability. Second, observe that when the CUs use three radios, the forced termination probability is smallest. This is because as the number of radios increases, the probability that a CU is affected by a PU activity decreases. However, at some point the CUs might not be able to use all their radios due to band unavailability, thus we observe an increase in the forced termination probability as the number of radios in use is decreased. Unlike the blocking probability, the forced termination probability does not significantly depend on the channel assignment schemes we considered in this work since they all try to minimize the number of guard bands which results in having fewer frequency blocks, hence the same level of influence by PU activity.

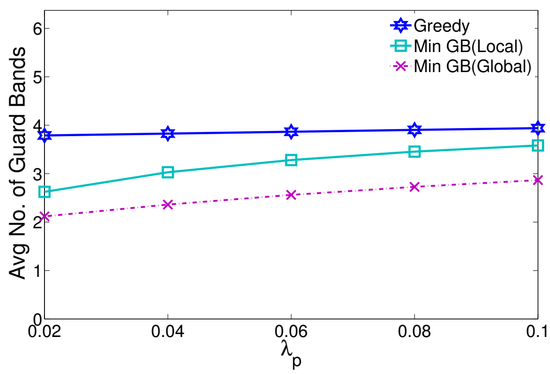
### *C. Impact of Guard Band Awareness on Spectrum Efficiency*

We study the impact of considering the guard bands on spectrum efficiency, defined as the ratio of the number of bands used for data transmission to total number of bands. Fig.3(a) depicts the spectrum efficiency as a function of the primary user arrival rate $\lambda_p$ and Fig. 3(b) depicts the spectrum efficiency as a function of the number of radios used by each cognitive user $m$ under three different channel assignment schemes.

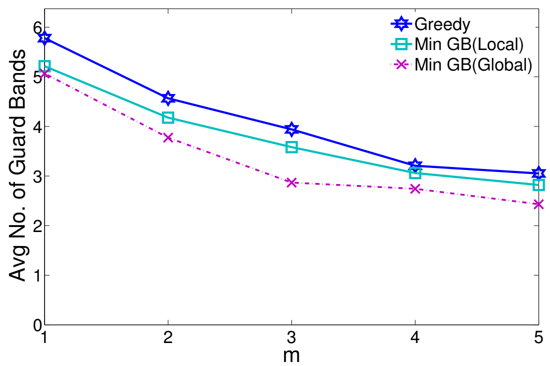
We make three observations. First, in Fig.3(a), observe that the spectrum efficiency does not depend on primary user arrival rate as expected. That is, when a the primary user arrival rate increases, the spectrum is used by the primary users instead of cognitive users, hence the number of bands used for transmission does not change rather the type of users change. Second, in Fig.3(b), observe that the spectrum efficiency increases as the number of radios used by each cognitive user increases. The reason is that fewer CUs may access the spectrum, hence the number of frequency blocks that are used by CU decreases, thus the number of required guard bands is less. Therefore, user may access the spectrum bands more efficiently. Third, the spectrum efficiency does not depend on the channel assignment schemes used in this work as they aim to deploy fewer guard bands.

### *D. Average Number of Guard Bands under Various Channel Assignment Schemes*

Last, we study the average number of guard bands used under the three different channel assignment schemes described in Section III. Spectrum efficiency as a function of the primary user arrival rate $\lambda_p$ is shown in Fig.4(a) while Fig.4(b) depicts the spectrum efficiency as a function of the number of radios used by each cognitive user $m$ under three




(a) Average Number of Guard Bands vs. $\lambda_p$




(b) Average Number of Guard Bands vs. $m$

Fig. 4. Average number of guard bands as a function of (a) the primary arrival rate $\lambda_p$ (b) the number of radios $m$, under three different channel assignment schemes ($\mu_p = 10$, $\lambda_c = 1$, $\mu_c = 10$, $n = 10$)

different channel assignment schemes.

First, we observe that, in Fig.4(a), as the primary user arrival rate $\lambda_p$ increases, the average number of guard bands increases due to not finding contiguous bands to use as a frequency block; hence CUs need to use more frequency blocks, demanding more guard bands. Second, in Fig.4(b), we observe that average number of guard bands decreases as the number of radios used by each CU increases. That is, increasing the number of radios helps the CUs to bond contiguous bands forming larger frequency blocks which requires fewer number of guard bands. Third, as expected, the channel assignment scheme, which intuitively reduces the number of guard bands, imposes fewer guard bands.

## VI. Concluding Remarks

In this paper, we proposed a continuous time Markov model for cognitive radio networks. Our model consider using non-ideal filters, thus requiring guard bands to prevent adjacent channel interference. In our model, we consider CUs that are capable of bonding and aggregating channels while having multiple radios. Exploiting our proposed model, we derived and analyzed various network performance metrics. Specifically, we derived blocking and forced termination probabilities of CUs as well as spectrum efficiency and the average number of required guard bands. In our analysis, we compared three different channel assignment schemes. Our analysis showed that disregarding adjacent channel interference (ACI) results in inaccurate and misleading outcomes.

## VII. Acknowledgements

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