Forced Spectrum Access Termination Probability Analysis Under Restricted Channel Handoff

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Abstract. Most existing works on cognitive radio networks assume that cognitive (or secondary) users are capable of switching/jumping to any available channel, regardless of the frequency gap between the target and the current channels. Due to hardware limitations, cognitive users can actually jump only so far from where the operating frequency of their current channel is, given an acceptable switching delay that users are typically constrained by. This paper studies the performance of cognitive radio networks with dynamic multichannel access capability, but while considering realistic channel handoff assumptions, where cognitive users can only move/jump to their immediate neighboring channels.
Specifically, we consider a cognitive access network with m channels in which a cognitive user, currently using a particular channel, can only switch to one of its k immediate neighboring channels. This set of $2k$ channels is referred to as the *target handoff channel set*. We first model this cognitive access network with restricted channel handoff as a continuous-time Markov process, and then analytically derive the forced termination probability of cognitive users. Finally, we validate and analyze our derived results via simulations. Our obtained results show that the forced access termination probability of cognitive users decreases significantly as the number k increases.

1 Introduction

Dynamic spectrum access or cognitive radio access network paradigm allows cognitive (or secondary) users (CUs) to exploit unused licensed spectrum on an instant-by-instant basis, so long as it causes no harm to primary users (PUs). That is, CUs must make sure that the licensed band is vacant before using it, and must vacate the band immediately upon the return of any PUs to their licensed band.

Cognitive radio has great potential for improving spectrum efficiency and increasing achievable network throughput of wireless communication systems. As a result, it has generated significant research interests and resulted in numerous papers over this past decade. The research issues and topics that have been addressed in recent years in this regard are also numerous, ranging from fundamental networking issues to practical and implementation ones. Examples of investigated issues pertaining to cognitive networking, just to name a few, are performance modelling and characterization [3, 14, 15], spectrum access management [2, 4, 19], adaptive and learning technique development [5, 12, 16, 21], network architectures [9, 17, 18], spectrum prediction models [1, 10, 11], and protocol design [6, 13, 20]. One common shortcoming with most existing works on cognitive radio networks is that it is almost always assumed that cognitive (or secondary) users are capable of switching/jumping to any available channel, regardless of the frequency gap between the target channel and the current channel. This is not realistic [7, 8]. Due to hardware limitations, cognitive users can actually jump only so far from where the operating frequency of their current channel is, given an acceptable switching delay that users are typically constrained by [7, 8]. This paper studies the performance of cognitive radio networks, but while considering realistic channel handoff/switching assumptions, where CUs can only move/jump to channels that are immediate neighbors of their current operating channels.

The focus of this work is then on cognitive wireless networks that are enabled with dynamic multichannel access, but with limited channel handoff/switching capability. Specifically, we consider a cognitive access network with m channels in which a cognitive user, currently using a particular channel and needing to vacate it due for e.g. to the return of its PUs, can only switch to one of its k immediate (from above and below) neighboring channels. This set of $2k$ channels is referred to as the *target handoff channel set*.

In this paper, we first model the cognitive access network with restricted channel handoff as a continuous-time Markov process. Then, we analytically derive the forced access termination probability of cognitive users, defined as the probability that a CU, already accessing and using a channel whose PU is returned, is forced to cease communication as a result of none of the channels in its target handoff channel set is vacant. Finally, we validate and analyze our derived results via MATLAB simulation. Our results show the impact of the channel handoff restriction in cognitive radio access on the probability of users being forced to terminate access to the system. Our obtained results show that the forced access termination probability of cognitive users decreases significantly as the number of target handoff channels increases for a fixed primary user load. The results also show that the gap between the forced termination probabilities for different numbers of target handoff channel set sizes increases with the primary user arrival rate.

To summarize, our contributions in this work are: 1) performance modelling of cognitive radio network access with limited spectrum handoff, 2) validation of our derived analytic results via simulations, and 3) study and analysis of the impact of spectrum handoff restriction on the performance behaviors of cognitive radio networks with multichannel access capability.

The rest of the paper is organized as follows. In Section 2, we state the system model. In Section 3, we model and derive analytically the forced termination probability. Section 4 validates the derived results, and analyzes the performance behaviors. Finally, in Section 5, we conclude our work.

2 Multichannel Access Model

We consider a cognitive radio multichannel access system with m primary bands, B_1,...,B_m, where each band is composed of n sub-bands, giving a total of mn sub-bands, termed A_1,...,A_{mn}. Two types of users are present in the system. Primary users (PUs) who have exclusive access rights to B_1 to B_m, and cognitive users (CUs) who are allowed to use the A_1 to A_{mn} sub-bands, but in an opportunistic manner; i.e., so long as they do not cause any harmful interference to PUs. While PUs have strict priority to use the spectrum bands, CUs are allowed to use a sub-band only when the sub-band's associated primary band is vacant; i.e., not being used by any PUs. Thus, we assume that CUs are always aware of the presence of PUs, and that as soon as any PUs reclaim their band, CUs are capable of immediately vacating the band and switch to another idle sub-band, if any exists. This is called spectrum handoff [22]. In our model, we assume that, during spectrum handoff, CUs can jump to any channel/band situated at no more than k bands away from its current operating band; the set of possible channels to which a CU is able to jump to is referred to as the *target handoff channel set*. Specifically, if an CU is currently using a sub-band belonging to primary band B_i, the CU can only jump to any sub-band from B_{i-k} to B_{i+k} when handoff is initiated. The number k is called the steps that a cognitive user is able to jump in each spectrum handoff.

3 Performance Modelling

We model the channel selection process as a continuous-time Markov process. The process is defined by its states and transition rates. In this section, we define the states and calculate the state transition rates.

As stated previously, mn sub-bands are shared by both primary and cognitive users. Thus, we define each state as an m-tuple $(i_1, ..., i_m)$ in which i_j, for $j = 1, 2, \ldots, m$, indicates the number of CUs in band j if $i_j > -1$, otherwise i_j is equal to -1, indicating that band j is occupied by a primary user. Note that i_j takes on values between -1 and n (i.e., $-1 \leq i_j \leq n$). Thus, the total number of states is $(n+2)^m$ and all these states are valid.

We assume that arrivals of cognitive users and primary users both follow Poisson processes with arrival rates λ_c and λ_p, respectively, and the service times are exponentially distributed with rates μ_c and μ_p, respectively.

There are four cases/events under which a state changes, and thus we only have to consider these four cases to compute the transition rate matrix, known as Q. In what follows, let $(i_1, ..., i_m)$ be the current state.

Case 1: First, consider that a cognitive user arrives to the system and selects spectrum band j. The next possible states are then $(i_1, ..., i_j + 1, ..., i_m)$ for all $-1 < i_j < n$. Assuming that the number of these states is l, the transition rate from $(i_1, ..., i_m)$ to $(i_1, ..., i_j + 1, ..., i_m)$ is then λ_c/l. The states whose i_j value is either -1 or n do not change, because the cognitive user will be blocked and denied access to the system in this case.

Case 2: Second, consider that a cognitive user leaves spectrum band j. In this case, the next possible states are $(i_1, ..., i_j - 1, ..., i_m)$ for all $i_j > 0$. Thus, the transition rates from $(i_1, ..., i_m)$ to $(i_1, ..., i_j - 1, ..., i_m)$ is $i_j \mu_s$.

Case 3: Third, when a primary user leaves band j, the next states are $(i_1, ..., i'_j, ..., i_m)$ where $i'_j = 0$ and $i_j = -1$. Assuming that the number of occupied bands by primary users is l which means that the number of next states is l, the transition rate from $(i_1, ..., i_m)$ to $(i_1, ..., i'_j, ..., i_m)$ is then μ_p/l, where as stated earlier $i'_j = 0$ and $i_j = -1$.

Case 4: Fourth, consider that a primary user arrives to spectrum band j. Note that primary users do not select any band upon their arrivals, since they already have their predefined bands to operate on. In this case, the next states are $(i_1, ..., i'_{j-k}, ..., i'_j, ..., i'_{j+k}, ..., i_m)$ where $i'_j = -1$ and $\left(\sum_{l=j-k, l \neq j}^{j+k} i'_l = i_j\right)$ if user is not forced to terminate. User access termination occurs when none of the adjacent bands can accommodate the cognitive user that is required to vacate band j. Thus, the next states are $(i_1, ..., i'_{j-k}, ..., i'_j, ..., i'_{j+k}, ..., i_m)$ where $i'_j = -1$ and $i'_l = n$ for $i - k \leq l \leq i + k$. When the user is forced to terminate, the transition rate is λ_p, and when there is no termination, the transition rate is as follows

$$\gamma^s_{s'} = \lambda_p \left(\frac{1}{2k - \sum\limits_{l=j-k, i'_l=-1}^{j+k} 1} \right)^{i_j} \prod_{l=0, l \neq k}^{2k} \binom{i_j}{i'_{j-k+l} - i_{j-k+l}} \tag{1}$$

where $\gamma^s_{s'}$ denotes the transition rate from state s to state s', where $s = (i_1, ..., i_m)$ and $s' = (i'_1, ..., i'_m)$. Thus far, we computed the transition rates, and we were able to determine the transition matrix Q. One can now solve the system of equations

$$\pi.Q = 0 \text{ and } \sum_{i=1}^{(n+2)^m} \pi_i = 1$$

where π_i is the stationary probability of state i and π is the stationary probability matrix.

Now, the forced termination probability P_f of a cognitive user can be defined as

$$P_f = \frac{\sum\limits_{(s,s')\in T} \pi_s \gamma^s_{s'}}{(1 - P_b)\lambda_c} \tag{2}$$

where T is the set that contains all state pairs (s, s') in which a user is forced to terminate when transitioning from s to s', and P_b is the blocking probability to be defined later. Formally, T can be defined as

$$T = \{(s, s') = ((i_1, ..., i_m), (i'_1, ..., i'_m))|N_c(s) > N_c(s') \textit{ and } N_p(s) < N_p(s')\}$$

where $N_c(s)$ and $N_c(s')$ are the numbers of cognitive users in state s and s', respectively, and $N_p(s)$ and $N_p(s')$ are the numbers of primary users in state s and s', respectively. The number of cognitive users in state $s = (i_1, ..., i_m)$, $N_c(s)$, can be written as

$$N_c(s) = \sum_{j=1, i_j \neq -1}^{m} i_j$$

Similarly, the number of primary users in state $s = (i_1, ..., i_m)$, $N_p(s)$, can be written as

$$N_p(s) = \sum_{j=1, i_j = -1}^{m} 1$$

When a new cognitive user arrives to the system and cannot find any empty sub-band, because the bands are occupied by primary users or any other cognitive users, the user is denied access to the system. In this case, we say that the user is blocked. The blocking probability P_b of a cognitive user trying to access the system can then be written as

$$P_b = \sum_{s\in B} \frac{\pi_s \lambda_c}{\sum\limits_{s\in S, s\neq s'} \gamma^s_{s'}} \tag{3}$$

where B is the set of all the states in which blocking occurs when a new cognitive user arrives to the system, and is defined as

$$B = \{s = (i_1, ..., i_m)|\forall j \;\; 1 \leq j \leq m, \;\; -1 < i_j < n\}$$

4 ANALYSIS AND VALIDATION

In this section, we validate our analytic results via MATLAB simulations, and analyze the performance of cognitive radio systems with multichannel access capabilities by studying the impact of the target handoff channel set size on the forced termination probability. For this, we consider evaluating a multichannel access cognitive system with $m = 7$ primary bands, each having $n = 2$ sub-bands.

Fig.1 plots the forced termination probability of cognitive users that we analytically derived in this work as a function of the primary user arrival rate λ_p for three different values of the number of

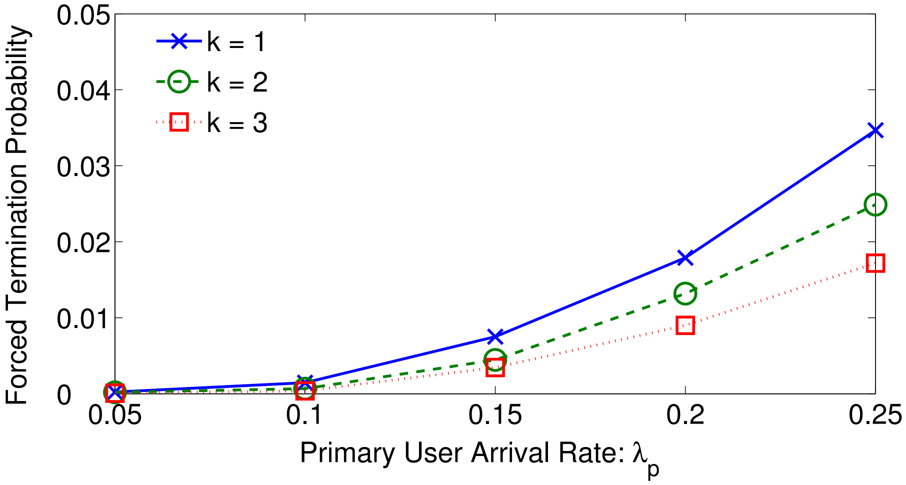

Fig. 1. Analytic results: forced termination probability as a function of the primary arrival rate λ_p for $k = 1, 2, 3$.

target handoff channels, k. First and as expected, observe that as the primary user arrival rate (i.e., PU load) increases, the probability that cognitive users (already using the system) are forced to leave the system due to not finding an available band in their target handoff channel set increases. Second, for a given primary user arrival rate λ_p, the greater the number of target handoff channels, the lower the forced termination probability. Again, this trend of performance behavior is expected, as having more channels to switch to increases the chances of cognitive users finding available bands, which explains the decrease in the forced termination probability of cognitive users. Third, the gap between the forced termination probabilities for different numbers of target handoff channel set sizes increases with the primary user arrival rate.

Now that we investigated the performance behaviors of cognitive radio systems through the derived analytic results, we next focus on validating these derived models. For this we use MATLAB to simulate a multichannel system with primary and cognitive users arriving to the system according to Poisson process with arrival rates λ_p and λ_c, respectively. In these simulations, we compute the actual forced termination probability of cognitive users, measured as the ratio of the number of terminated users to the total number of accepted users. Fig. 2 shows the values of forced termination probabilities of the simulated cognitive network again for three values of k. Observe that the simulated performance behaviors of cognitive systems in terms of the forced termination probability match well those obtained via our analytically derived results. This validates our derived models.

To summarize, our findings in this work demonstrate the impact of the commonly made assumption of considering that cognitive users are able to handoff/switch to any available band, regardless of how far the target band is from the current band, on the performance behaviors of cognitive radio systems. Our results show the importance of considering realistic spectrum handoff (i.e., with restricted/limited target handoff channel set) when assessing the achievable cognitive radio performances. Although the performance metric investigated in this work is the forced access termination probability of cognitive users already using the system, one can easily project this analysis on other performance metrics, such as the per-user achievable throughput and user blocking probability, which are kept for future investigation.

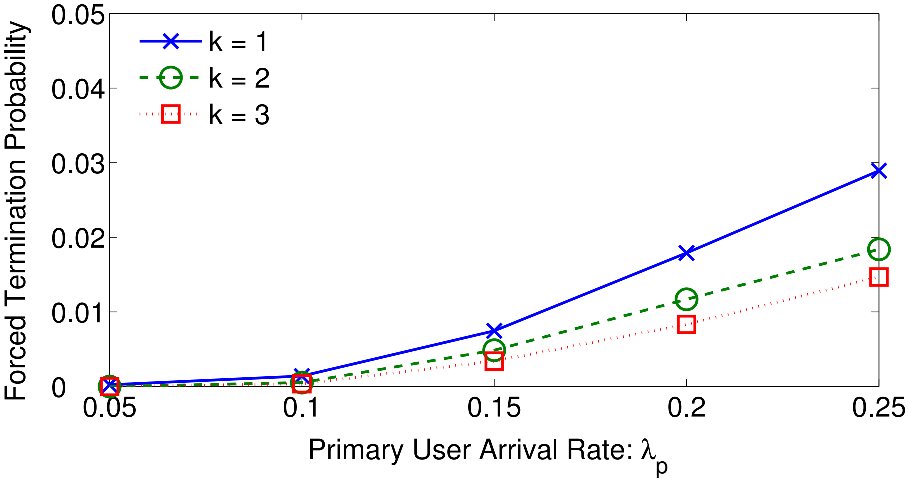

Fig. 2. Simulation results: forced termination probability as a function of the primary arrival rate λ_p for $k = 1, 2, 3$.

5 Conclusion

This paper investigates the performance behaviors of cognitive radio networks enabled with dynamic multichannel access, but while considering realistic channel handoff assumptions, where cognitive users are only allowed to switch to vacant channels that are immediate neighbors of their current channels. Using Markovian analysis, we model cognitive access networks with restricted channel handoff as a continuous-time Markov process, and analytically derive the forced access termination probability of cognitive users that are already using the system. Using MATLAB, we also validate our derived results via simulations.

Our obtained results demonstrate the impact of considering realistic channel handoff restriction in cognitive radio access on the probability of cognitive users being forced to terminate access to the system, and show that the forced access termination probability decreases significantly as the number of target handoff channels increases. This work demonstrates the cognitive radio performance implications of the commonly made assumption of allowing cognitive users to switch to any available band, regardless of how far the target band is from the current band. These performance implications translate in terms of forced access termination probability as well as long-term achievable throughput and access blocking probability of cognitive users.

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