Optimal Admission Control in Cognitive Radio Networks

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***Abstract*—We study a cognitive radio system in which the spectrum handover technique is applied by secondary users when they have to vacate a channel due to a primary user arrival. In order to limit the forced termination probability of secondary users a fractional guard channel reservation scheme is applied to give priority to spectrum handovers over new arrivals.**

We show that, contrary to what has been suggested, the reservation parameter cannot be adequately adjusted as a result of maximizing the throughput of secondary users. Instead we propose and explore two alternative configuration methods. The proposed methods are based on optimization problems that target the existing trade-off between blocking new sessions of secondary users and dropping ongoing ones. Additionally in our numerical experiments we identify some interesting and counterintuitive phenomena.

I. INTRODUCTION

Cognitive Radio (CR) networks are envisaged as the key technology to realize dynamic spectrum access. Such paradigm shift in wireless communications aims at solving the scarcity of radio spectrum [1], [2].

The problem of spectrum scarcity is, at least in part, the result of, or is exacerbated by, the long-running static spectrum allocation policies, which are based on assigning spectrum bands to license holders on a long-term basis for large geographical regions. While there is an increasing demand of spectrum, those spectrum management policies have lead to an important underutilization (both temporally and spatially) of a big part of the assigned bands: conducted spectrum occupancy measurement studies yield average utilization figures as low as 5.2% [3], and below 20% in big cities such as New York or Chicago [4].

The CR concept proposes to boost spectrum utilization by allowing CR users (secondary users) to access the licensed wireless channel in an opportunistic manner so that interference to licensed users (primary users) is kept to a minimum.

The idea of CR is undoubtedly compelling and its realization will induce a huge advance in wireless communications. However, there are many challenges and open questions that have to addressed before CR networks become practically realizable [5], [6].

From a traffic management standpoint there is a need to develop new models and perform numerical analyses that help to unveil new phenomena, and to better understand the dynamics of such systems.

To fulfill the requirement of minimum interference to primary users (PUs), a secondary user (SU) with an ongoing communication must vacate the channel when a licensed user is detected. To prevent the SU from dropping its ongoing session it may switch to a different unused spectrum band, which is referred to as spectrum mobility or *spectrum handover* (SH). If no available bands can be found or the SH procedure is not implemented, one o more SUs will be forced to terminate their sessions.

The queuing literature studies about systems with two or more classes of customers where one has preemptive priority over the other, date back at least to the sixties, see [7], [8] and references therein. However, the topic is far from being closed and most, if not all, of the existing results assume that customer of all classes share the same service time distribution and/or each user consumes the same amount of resources regardless of its class. In general those assumptions are not suitable for CR systems since user type heterogeneity is an inherent characteristic of such systems. Furthermore, relaxing the homogeneity assumptions can render the model intractable [8]. It is thus necessary to develop new simple models that help to gain an insight into the behavior of CR systems and serve as a first approximation to their design and configuration. Based on the obtained knowledge and experience more sophisticated and precise methods should be subsequently developed.

On the other hand, a variety of studies that focus on priority mechanisms to handle conventional handovers in cellular networks have appeared in the literature, see [9] and references therein. Notwithstanding, SH and conventional handover are different in nature and also from a modeling perspective.

In this paper we focus on the study of the Quality of Service (QoS) seen by secondary users at the session level. As mentioned above, if a PU starts using a channel that is occupied by a SU the latter may be forced to terminate its ongoing sessions unless a SH to an unused channel is performed. From a user perspective, it is generally assumed that the interruption of an ongoing session is more annoying than denying initial access. Therefore, blocking the request of a new SU session, even if there are enough free channels, can be employed as a strategy to lessen the number of SU sessions forcedly terminated. By employing that approach a trade-off naturally arises between the probability of blocking and the probability of forced termination. Our purpose here is to gain insight into the effect that system parameters have on those two performance parameters of a CR network and, based on that, propose design criteria in order to balance adequately the conflicting requirements.

We employ the same rather simple model than [10], which is enhanced to include an extension of the reservation scheme so that a non-integer number of channels can be reserved for SH. Such extension borrows the idea from the fractional guard channel scheme that was introduced in cellular networks [11]. The greater flexibility of using a continuous configuration parameter instead of being constrained to a discrete one is expected to allow a more efficient use of resources.

Furthermore, our numerical results for the system throughput are qualitatively different from those obtained in [10] leading to completely different conclusions, especially in what concerns the optimum system configuration. We propose two alternative configuration rules and show that, for both of them, an optimum value for the reservation parameter exists. These optimization criteria had already been employed in cellular networks to balance the trade-off that arises between blocking new sessions and handover requests [11], [12].

The rest of the paper is structured as follows. The model of the system is described in Section II. In Section III it is numerically studied the impact that varying the reservation parameter has on the QoS of SU's. From the results in that section we conclude that for the studied model, the throughput of SU's does not offer a valid criteria for adjusting the configuration of the system. Two alternative configuration criteria are proposed and analyzed in sections IV and V. Finally, Section VI concludes the paper.

II. MODEL DESCRIPTION

The system has a total of C resource units, being the physical meaning of a unit of resource dependent on the specific technological implementation of the radio interface. We study a single service scenario.

For the sake of mathematical tractability we make the common assumptions of Poisson arrival processes and exponentially distributed service times. The arrival rate for PU (SU) sessions to the system is λ_1 (λ_2), and a request consumes b_1 (b_2) resource units when accepted, $b_i \in \mathbb{N}$, $i = 1, 2$. For a packet based air interface, b_i represents the effective bandwidth of the session [13], [14]. We assume that $b_1 = N$, $b_2 = 1$ and that $C = M \times N$, therefore the system resources can be viewed as composed by $M = C/N$ bands for PUs or $M \times N$ sub-bands for SUs. The service rates for primary and secondary sessions is denoted by μ_1 and μ_2 respectively.

We develop two analytical models to evaluate the performance of systems with and without spectral handover. We denote by $\boldsymbol{x} = (x_1, x_2)$ the system state vector, when there are x_1 ongoing sessions of PUs and x_2 of SUs. Let $b(\boldsymbol{x})$ represent the amount of occupied resources at state $\boldsymbol{x}$, $b(\boldsymbol{x}) = x_1 N + x_2$. The system evolution along time can be modeled as a multidimensional birth-and-death process. The set of feasible states for the process is

$$\mathcal{S} := \{\boldsymbol{x} = (x_1, x_2) : x_1 N + x_2 \le C\}.$$

A. System Without Spectral Handover

A PU arrival in state $\boldsymbol{x}$ will force the termination of k SUs, $k = 0, \ldots, \min(x_2, N)$, with probability

$$p(\boldsymbol{x}, k) = \frac{\binom{N}{k}\binom{(M-x_1-1)N}{x_2-k}}{\binom{(M-x_1)N}{x_2}}$$

when k SUs are in the sub-bands occupied by the newly arrived PU session, while the other $(x_2 - k)$ are distributed in the other $N(M - x_1 - 1)$ sub-bands. Clearly,

$$\sum_{k=0}^{\min(x_2,N)} p(\boldsymbol{x}, k) = 1 \; .$$

Let $r_{\boldsymbol{xy}}$ be the transition rate from $\boldsymbol{x}$ to $\boldsymbol{y}$, $\boldsymbol{x} \in \mathcal{S}$, and be $\boldsymbol{e}_i$ a two dimensional vector with position i set to 1 and the other position set to 0, then

$$r_{\boldsymbol{xy}} = \begin{cases} a_1(\boldsymbol{x})\,\lambda_1 & \text{if } \boldsymbol{y} = \boldsymbol{x} + \boldsymbol{e}_1 - k\boldsymbol{e}_2, \\ a_2(\boldsymbol{x})\,\lambda_2 & \text{if } \boldsymbol{y} = \boldsymbol{x} + \boldsymbol{e}_2, \\ x_i \mu_i & \text{if } \boldsymbol{y} = \boldsymbol{x} - \boldsymbol{e}_i, \\ 0 & \text{otherwise} \end{cases}$$

It is obvious that $a_1(\boldsymbol{x}) = p(\boldsymbol{x}, k)$, if $\boldsymbol{x} + \boldsymbol{e}_1 - k\boldsymbol{e}_2 \in \mathcal{S}$, and 0 otherwise. Similarly, $a_2(\boldsymbol{x}) = 1$, if $\boldsymbol{x} + \boldsymbol{e}_2 \in \mathcal{S}$, and 0 otherwise. Figure 1 shows the state diagram and transition rates of the continuous-time Markov chain (CTMC) that models the system dynamics. The global balance equations can be expressed as

$$\pi(\boldsymbol{x}) \sum_{\boldsymbol{y}\in\mathcal{S}} r_{\boldsymbol{xy}} = \sum_{\boldsymbol{y}\in\mathcal{S}} \pi(\boldsymbol{y})\, r_{\boldsymbol{yx}} \quad \forall \boldsymbol{x} \in \mathcal{S} \tag{1}$$

where $\pi(\boldsymbol{x})$ is the state $\boldsymbol{x}$ stationary probability. The values of $\pi(\boldsymbol{x})$ are obtained from (1) and the normalization equation.

From the values of $\pi(\boldsymbol{x})$ the blocking probability for SUs requests P_2 and their forced termination probability P_2^{ft} can be determined. Let us define

$$k(\boldsymbol{x}) = \sum_{r=0}^{\min(x_2,N)} r p(\boldsymbol{x}, r)$$

then,

$$P_2 = \sum_{\boldsymbol{x}\in\mathcal{S}} (1 - a_2(\boldsymbol{x}))\, \pi(\boldsymbol{x}) \tag{2}$$

and

$$P_2^{ft} = \frac{\sum_{\boldsymbol{x}\in\mathcal{S}} k(\boldsymbol{x})\, \pi(\boldsymbol{x})\, \lambda_1}{\lambda_2 (1 - P_2)} \; . \tag{3}$$

Finally, the throughput of SUs, i.e. the successful completion rate of SUs is determined by

$$Th_2 = \lambda_2 (1 - P_2)(1 - P_2^{ft}). \tag{4}$$

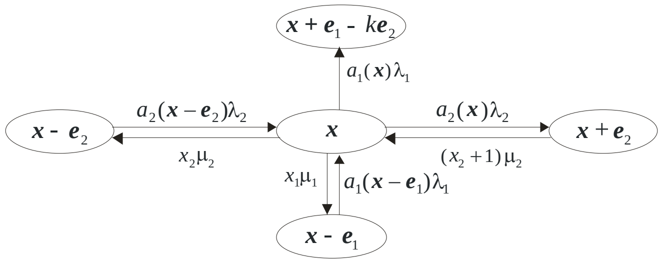

Fig. 1. State transition rates of the CTMC, $\boldsymbol{x} \in \mathcal{S}$.

B. System With Spectral Handover and Reservation

It is usually accepted that it is more disturbing for a subscriber in a cellular network to have an ongoing session dropped than the blocking of a new session setup. Then, to guarantee a certain degree of QoS to the SUs, we deploy the fractional guard channel admission policy. When a SU new setup request arrives to the system, an admission decision is taken according to the number of free resource units:

$$C - b\left(\boldsymbol{x} + \boldsymbol{e}_2\right) \begin{cases} > \lfloor t \rfloor & \text{accept} \\ = \lfloor t \rfloor & \text{reject with probability } t - \lfloor t \rfloor \\ < \lfloor t \rfloor & \text{reject} \end{cases}$$

where we denoted by $t \in [0, C]$, the admission control threshold, i.e. the average number of resource units that must remain free after accepting a new requests of SUs is t. Clearly, these resources are reserved for SUs performing spectral handovers. Then, the higher the t the lower the forced termination but the higher the blocking probability perceived by the new requests and vice versa. Note also that the PUs are unaffected by the admission policy, as SUs are transparent to them.

A PU arrival in state $\boldsymbol{x}$ will not force the termination of SUs when the system state complies with $C - b\left(\boldsymbol{x}\right) \geq N$, as the execution of spectral handover will allow to find new unused sub-bands. On the other hand, when $C - b\left(\boldsymbol{x}\right) < N$, $x_1 < M$, a PU arrival will preempt $b\left(\boldsymbol{x} + \boldsymbol{e}_1\right) - C$ SUs. Let $k\left(\boldsymbol{x}\right)$ be the number of preemptions in state $\boldsymbol{x}$, then

$$k\left(\boldsymbol{x}\right) = \min\{0, \ldots, N \mid b\left(\boldsymbol{x} + \boldsymbol{e}_1 - k\left(\boldsymbol{x}\right)\boldsymbol{e}_2\right) \leq C\}$$

Note that $k\left(\boldsymbol{x}\right) = 0$ when $C - b\left(\boldsymbol{x}\right) > N$, i.e. it will be null for a high portion of the state space.

As before, let $r_{\boldsymbol{xy}}$ be the transition rate from $\boldsymbol{x}$ to $\boldsymbol{y}$, $\boldsymbol{x} \in \mathcal{S}$, then

$$r_{\boldsymbol{xy}} = \begin{cases} a_1\left(\boldsymbol{x}\right)\lambda_1 & \text{if } \boldsymbol{y} = \boldsymbol{x} + \boldsymbol{e}_1 - k\left(\boldsymbol{x}\right)\boldsymbol{e}_2, \\ a_2\left(\boldsymbol{x}\right)\lambda_2 & \text{if } \boldsymbol{y} = \boldsymbol{x} + \boldsymbol{e}_2, \\ x_i\mu_i & \text{if } \boldsymbol{y} = \boldsymbol{x} - \boldsymbol{e}_i, \\ 0 & \text{otherwise} \end{cases}$$

The coefficients $a_1\left(\boldsymbol{x}\right)$ and $a_2\left(\boldsymbol{x}\right)$ denote the probabilities of accepting a PU arrival and a SU arrival, respectively. It is clear that $a_1\left(\boldsymbol{x}\right) = 1$, if $\boldsymbol{x} + \boldsymbol{e}_1 - k\left(\boldsymbol{x}\right)\boldsymbol{e}_2 \in \mathcal{S}$, and 0 otherwise.

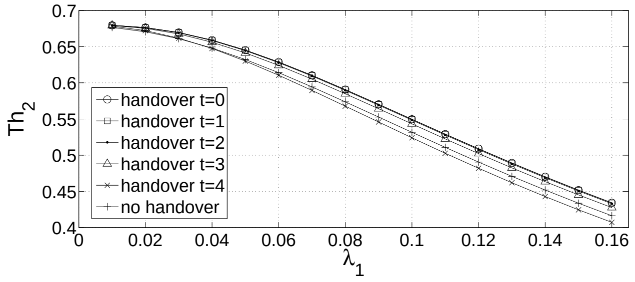

Fig. 2. Throughput with the arrival rate of primary users.

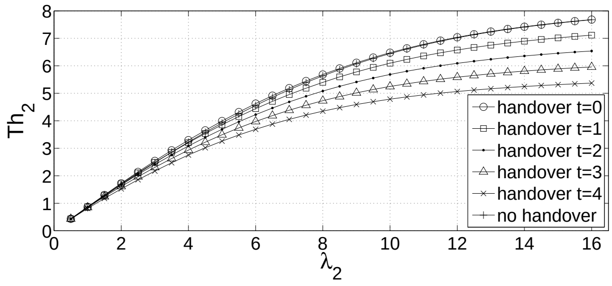

Fig. 3. Throughput with the arrival rate of secondary users.

Given a policy setting t, $a_2\left(\boldsymbol{x}\right)$ is determined as follows

$$a_2\left(\boldsymbol{x}\right) = \begin{cases} 1 & \text{if } C - b\left(\boldsymbol{x} + \boldsymbol{e}_2\right) > \lfloor t \rfloor \\ 1 - \left(t - \lfloor t \rfloor\right) & \text{if } C - b\left(\boldsymbol{x} + \boldsymbol{e}_2\right) = \lfloor t \rfloor \\ 0 & \text{otherwise} \end{cases}$$

Figure 1 shows the state transition rates of the CTMC that models the system dynamics.

By solving the global balance equations (1), together with the normalization equation, the values of $\pi\left(\boldsymbol{x}\right)$ can be obtained, and from them the blocking probability for SUs requests P_2, their forced termination probability P_2^{ft} and the SUs throughput Th_2 can be determined using (2), (3) and (4).

In the following Sections we evaluate the performance of a system with spectral handover and another without it, besides we propose two ways to perform the system configuration, i.e. to set t. For the numerical results, unless otherwise specified, we deploy the following reference scenario: $M = 3$, $N = 6$, $C = MN = 18$, $\lambda_1 = 0.08$, $\lambda_2 = 0.68$, $\mu_1 = 0.06$ and $\mu_2 = 0.82$.

III. SECONDARY USERS THROUGHPUT AND FORCED TERMINATION

Figure 2 and Fig. 3 show the throughput of SUs as a function of the arrival rate of primary and SUs respectively. For each of the two figures we also show the impact of reservation. Figure 4 shows the results obtained by simulating the system physical behavior. Note the excellent agreement between the analytical and simulation models. Although almost imperceptible, note also that confidence intervals for a confidence level of 95% have been depicted in the figure. The load region for the study in Fig. 2 has been chosen such that the traffic offered by PUs expressed in sub-bands varies from

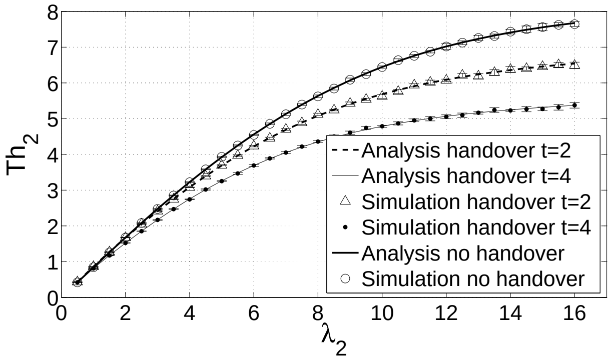

Fig. 4. Comparison of results from the analytical and simulation models.

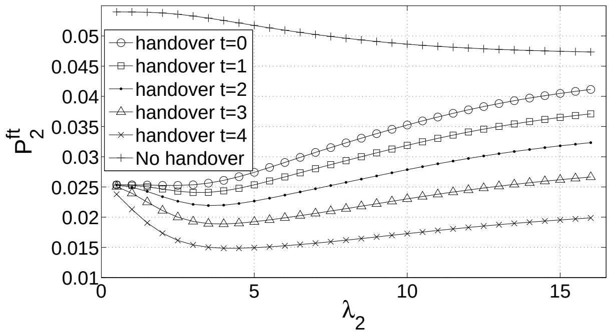

Fig. 5. Forced termination with the arrival rate of secondary users.

0 to 16 Er., while the offered by SUs is 0.83 Er. On the other hand in Fig. 3 the traffic offered by SUs expressed in subbands varies from 0 to 19.51 Er., while the offered by PUs is 8 Er.

The authors of [10] suggest that a natural way of configuring a cognitive radio system of similar characteristics is to choose t for each arrival rate of SUs such that their throughput is maximized. As observed in previous figures, it is not possible to determine an optimum operating point beyond the obvious one that is to deploy spectral handover and $t = 0$. The results confirm the intuition that increasing t beyond $t = 0$ to maximize the throughput has no sense. Guard channels have been classically deployed in cellular systems to limit the forced termination of accepted sessions and we believe that their role in cognitive radio systems is the same. Therefore the number of guard channels cannot be chosen to maximize the throughput of SUs. Clearly, the higher the number of guard channels the lower the forced termination probability but the higher the blocking probability of new requests, which might reduce the system revenue. In the following sections we explore alternative ways to perform the system configuration that take this trade-off into consideration.

On the most interesting results of the cognitive radio system studied is the evolution of the forced termination with the arrival rate of SUs shown in Fig. 5. Observe that it seems to have a counterintuitive behavior. Intuitively, one would expect that the forced termination would increase with the arrival rate of SUs. However in a system without spectral handover it has the opposite behavior. Note also that in a system with reservation and particularly for some reservation values like $t = 3$ or 4, the forced termination first decreases, attaining a minimum, and then increases. These phenomena can be explained as follows.

As in the scenario of Fig. 5 the arrival rate of PUs is constant, then P_2^{ft} depends only on the ratio of forced terminations to accepted sessions. For a system without spectral handover, if we compare the evolution of the forced termination rate with the acceptance rate for the interval of arrival rates of interest, it is clear that the acceptance rate grows more quickly than the forced termination rate in the first half of the interval, while both rates tend to grow with a similar slope by the end of the second half of the interval. In other words, from the point of view of the acceptance rate, the first part of the interval is dominated by an almost blocking free behavior and therefore it grows almost linearly with the arrival rate. In the second half the blocking starts to grow and the acceptance rate tends to stabilize by the end of the interval. This behavior is alike the one in Erlang systems, where the carried traffic increases linearly with the arrival rate up to a point beyond which it tends asymptotically to the system capacity.

When the system does support spectral handovers and the SUs arrival rate is low, most of the users are accepted in the system and the forced terminations are almost inexistent. As the arrival rate increases, the number of unsuccessful spectral handovers start to grow or equivalently the number of forced terminations start to grow. This point can be identified in Fig. 5 as the one where the negative slope of P_2^{ft} starts to decrease. As the arrival rate keeps on increasing, the slope of the acceptance rate starts to decrease while forced termination rate is maintained. This causes the slope of P_2^{ft} to change sign and to start growing on the positive side. Note that this behavior is magnified when the system deploys reservation.

IV. SYSTEM CONFIGURATION BY MINIMIZING A COST FUNCTION

We define the cost function

$$\gamma = P_2^n + \beta P_2^{ft}$$

where β allows the operator to weight adequately the cost of forced terminations against the cost of blocking SUs, i.e. a forced termination is β times more costly than a blocking. Our objective is to determine the value of t that minimizes γ.

For the reference scenario defined in Section II, Fig. 6 shows the optimum value of t as a function of the arrival rate of PUs for different values of β. For the load region of study, the optimum t takes values in the multiples of N. Ramjee et al. showed in [11] that in a cellular system with two arrival types, new and handovers, the optimal policy is of the guard channel type when the problem is formulated as the unconstraint minimization of a cost function that is a linear combination of the blocking probabilities for new and handover arrivals. In other words, the optimal policy is of the threshold type, where states for which the number of free resource units is higher than the threshold have associated

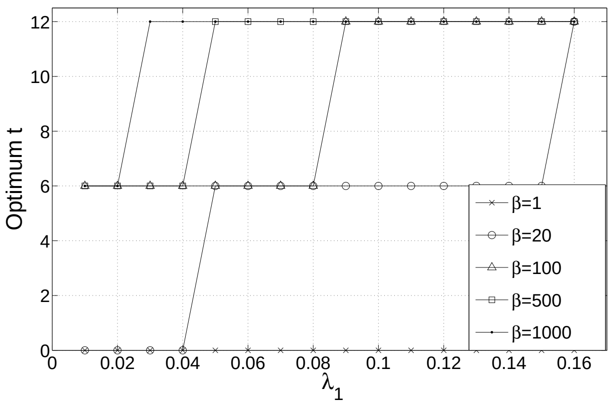

Fig. 6. Optimum t as a function of the arrival rate of primary users.

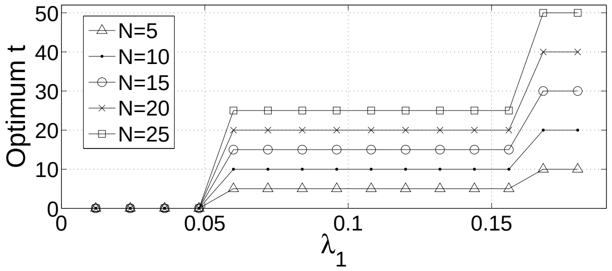

Fig. 7. Optimum t for different values of the number of sub-bands N required to a carry a primary user session.

acceptance actions, when it is equal or lower than the threshold have associated rejection actions and the threshold is a positive integer. Note that our context is completely different to the one studied in [11]. In our system, the mean service times and the number of resources occupied by the sessions of the two arrival streams are different. Nevertheless, our results show an empirical evidence that the conclusions of [11] might be also applicable here. Then, for the load region of interest when the primary arrivals consume N resource units, reserving non multiples of N resource units for secondary arrivals clearly has no impact. This phenomenon needs further investigation.

Figure 7 shows the variation of the optimum t as a function of the arrival rate of PUs for different values of N and when $\beta = 20$. As observed, the optimum reservation pattern follows the same rule given before.

Figure 8, Fig. 9 and Fig. 10 show, respectively, the throughput, blocking probability and probability of forced termination for SUs as a function of the arrival rate of PUs for different values of N when $\beta = 20$. Note that for each value of λ_1 and N the optimum t is deployed and that discontinuities are clearly visible when the value of t changes. Observe also that SUs performance parameters are almost unaffected by the value of N. When performing a zoom of some parts of the figures, one observes differences in the fourth or fifth decimal which are clearly negligible.

Figure 11 displays the optimum value of t as a function of the arrival rate of SUs for different values of β. Note that depending on the value of β now the optimum t is not a multiple of N and that, as in Fig. 6, the bigger the β the more costly are the forced terminations, and therefore the higher the amount of resource units the system reserves to prevent this from occurring. Note also that for $\beta = 20$ and $\beta = 30$ the optimum t has a counterintuitive behavior as it decreases when λ_2 increases and then, as λ_2 increases further, t increases. This is due to the non-monotonic shape of the cost function γ in the load region of study, but it requires more investigation to understand the intuition of the behavior.

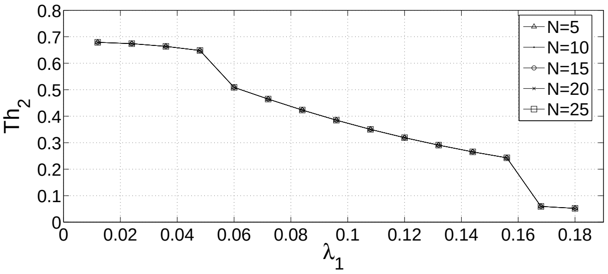

Fig. 8. Throughput when deploying the optimum t.

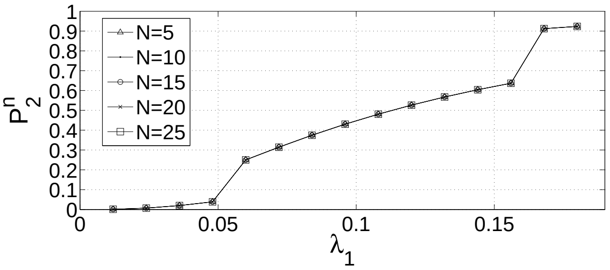

Fig. 9. Blocking probability when deploying the optimum t.

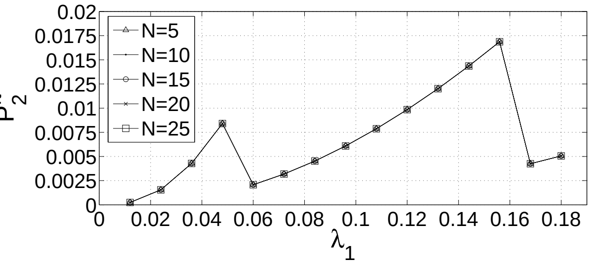

Fig. 10. Forced termination probability when deploying the optimum t.

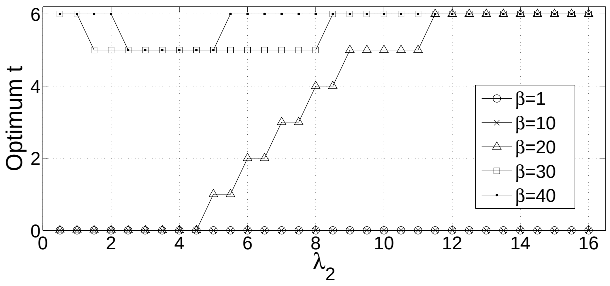

Fig. 11. Optimum t as a function of the arrival rate of secondary users.

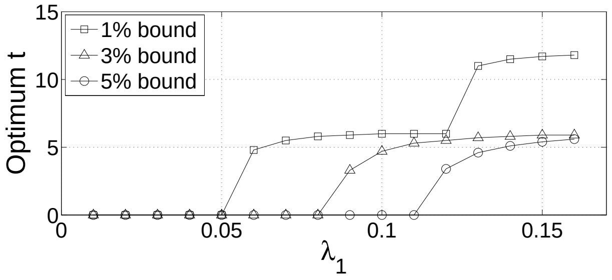

Fig. 12. Optimum t as a function of the arrival rate of primary users.

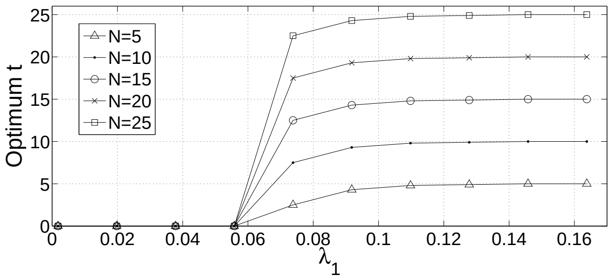

Fig. 13. Optimum t for different values of the number of sub-bands required to a carry a primary user session N.

V. System configuration by bounding the forced termination probability

We explore now the optimal configuration of t when the QoS objective is to guarantee a given bound for the forced termination probability of SUs. In this case, we intend to determine the value of t that minimizes the blocking probability of SUs, while guaranteeing a bound for their forced termination probability.

Figure 12 displays the optimum value of t as a function of the arrival rate of PUs for different bounds for the forced termination probability. Note that t takes now real values. Ramjee et al. showed in [11] that in a cellular system with two arrival types, new and handovers, the optimal policy is of the fractional guard channel type when the problem is formulated as the minimization of the blocking probability of new requests subjected to a constraint on the handover blocking probability. In other words, the optimal policy is of the threshold type, where states for which the number of free resource units is greater than $\lfloor t \rfloor$ have associated acceptance actions, when it is smaller than $\lfloor t \rfloor$ have associated rejection actions, when it is equal to $\lfloor t \rfloor$ have associated a randomized rejection action, and the threshold is a positive real. As stated in previous Section, note that our context is completely different to the one studied in [11] and, therefore, our results show an empirical evidence that the conclusions of [11] might be also applicable here. A more general result was obtained by Ross in [15], that showed that for the Markov decision problem of determining a policy to minimize the infinite-horizon average cost subject to K infinite-horizon average cost constraints in unichain systems, there exists an optimal solution with a degree of randomization no greater than K, i.e. it is never necessary to randomize in more than K states.

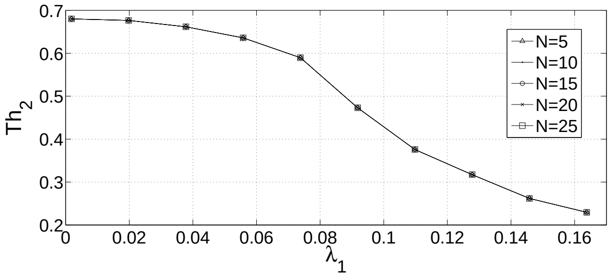

Fig. 14. Throughput when deploying the optimum t.

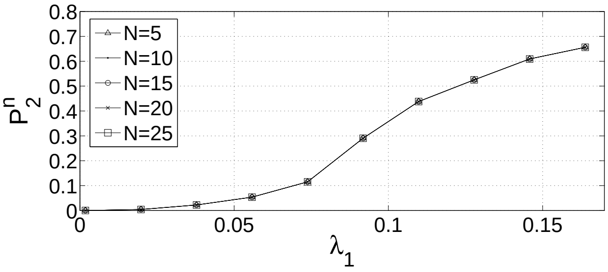

Fig. 15. Blocking probability when deploying the optimum t.

While keeping constant the arrival rate of SUs, Fig. 13 shows a similar reservation pattern to the one shown in the scenarios studied in Section IV, i.e. the system tends to reserve resources in the multiples of N, but while before the optimum t displays a step-wise shape, now the approximation to the multiples of N happens progressively as λ_1 grows.

As in previous Section, Fig. 14, Fig. 15 and Fig. 16 show, respectively, the throughput, blocking probability and probability of forced termination for SUs as a function of the arrival rate of PUs for different values of N. Recall that for each value of λ_1 and N the optimum t is deployed. Note that the constraint $P_2^{ft} \leq 0.02$ is always met and that the SUs performance parameters are unaffected by the value of N.

VI. Conclusions

We have studied a cognitive radio system in which SUs execute spectrum handovers if they have to vacate a channel due to a primary user arrival. In order to limit the forced termination probability of SUs a fractional guard channel reservation scheme is applied to give priority to spectrum handovers over new arrivals.

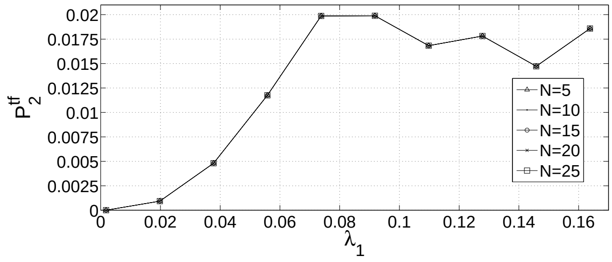

Fig. 16. Forced termination probability when deploying the optimum t.

A previous study showed that, for each system load, the number of guard channels could be configured to maximize the throughput of SUs in systems with spectral handover. We provide sufficient evidences that this approach does not achieve the intended objective. Even further, we believe that the role of guard channels in cognitive radio systems is the same as their classical role in cellular systems, i.e. to limit the forced termination probability of SUs.

Clearly there exits a trade-off between the forced termination probability and the blocking probability, i.e. the higher the number of guard channels the lower the forced termination probability but the higher the blocking probability of new requests, which might reduce the system revenue. Therefore, we propose and explore two ways of determining the optimum number of guard channels. One where the objective is to minimize a cost function that is a linear function of the blocking and forced termination probabilities. Another, where the objective is to minimize the blocking probability subject to a constraint on the forced termination probability.

During the study we illustrate how the behavior of a cognitive radio system displays new phenomena not previously encountered in other wireless systems. Some of them were discussed in the paper while other require further investigation.

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