Admission Control and Interference Management in Dynamic Spectrum Access Networks

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***Abstract*—Two of the important aspects that must be studied to make dynamic spectrum access work in practice are the admission policy of secondary users (SU), in order to achieve a certain degree of quality of service, and the management of the interference caused by SU to primary users (PU).**

In order to limit the forced termination probability of SU we evaluate a fractional guard channel reservation scheme to give priority to spectrum handovers over new arrivals. We show that, contrary to what has been suggested, the throughput of SU cannot be maximized by configuring the reservation parameter.

We also study the interference caused by SU to PU. We propose and evaluate mechanisms to reduce the interference based on simple spectrum access and channel repacking algorithms for both PU and SU. Numerical results show that, with the interference metric defined, the reduction can be of two orders of magnitude with respect to the random access case.

Finally, we propose an adaptive admission control scheme that is able to limit simultaneously both the forced termination probability of SU and what we define as the probability of interference. Our scheme is self-adaptive and does not require any configuration parameters beyond the probability objectives. Besides, it can operate with any arrival process and any distribution of the session duration and residence time.

I. Introduction

Cognitive radio networks are envisaged as the key technology to realize dynamic spectrum access (DSA). 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 DSA concept proposes to boost spectrum utilization by allowing DSA users (SU) to access the licensed wireless channel in an opportunistic manner so that interference to licensed users (PU) is kept to a minimum.

The idea of DSA 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 DSA networks become practically realizable [5], [6].

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

To fulfill the requirement of minimum interference to PU, 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 SU 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 DSA 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 DSA 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) perceived by SU at the session level. As mentioned above, if a PU initiates its communication deploying a channel that is occupied by a SU, the latter may be forced to terminate its ongoing session unless a SH to an unused channel can be 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.

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].

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.

Interference avoidance has been targeted as one of the critical challenges to make DSA work in practice [6]. Common DSA proposals take a reactive approach, in which SU perform SH only after detecting interference with PU. To detect a PU activity in the same band, a SU must perform *spectrum sensing*, which requires to pause any ongoing transmission and causes a considerable performance penalty [6]. On the other hand, SU must execute spectrum sensing frequently to react quickly when a PU occupies the same band. To manage these conflicting requirements, transmission and spectrum sensing episodes are interleaved typically in a cyclic manner [12].

We study the interference avoidance problem from a traffic perspective. Our perception is that the proposed mechanisms should have a complementary role with respect to those defined at the physical layer. Our work is motivated by the fact that although simple spectrum access and channel repacking algorithms have been proposed in the classical communications literature its application to DSA systems has not been explored jet. We define an spectrum access algorithm in which to setup a new PU session the system searches in the pool of available channels from left (low frequencies) to right (high frequencies) until enough free channels can be allocated to the new session. Conversely, to setup a new SU communication the system searches in the pool of available channels from right (high frequencies) to left (low frequencies). We call this mechanism *channel allocation with preference* (CAP).

Additionally, once a PU or a SU session has finished, a *channel repacking* of ongoing SU sessions can be performed to avoid interference with future PU arrivals. Channel repacking can be triggered when, after a session completion, there exist ongoing SU sessions that can be moved to higher frequency channels, i.e. there exist ongoing SU sessions that can perform a preventive SH to avoid creating future interference.

The rest of the paper is structured as follows. The different models of the systems studied are described in Section II. In Section III we evaluate numerically the impact of incorporating admission control on the forced termination of SU and also the impact of deploying channel allocation with preference and repacking. In Section IV we propose and evaluate a novel adaptive admission control scheme that is able to limit simultaneously both the forced termination probability and the interference. Finally, Section V 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.

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 PU or $M \times N$ sub-bands or channels for SU. The service rate for primary and secondary sessions is denoted by μ_1 and μ_2 respectively.

We study five different system scenarios that can be aggregated in three groups. With the first we evaluate the impact of incorporating an admission control policy on the QoS perceived by the SU, which is measured by their *forced termination probability*. With the second we evaluate the impact of incorporating a channel allocation preference and repacking on the interference perceived by the PU, which is measured by the *spectrum handover rate* induced by the arrival of new PU sessions. Finally, the last group allows us to evaluate the impact of incorporating an adaptive admission control scheme that is able to limit simultaneously both a measure of the forced termination probability of SU and a measure of the SH rate induced by the arrival of PU.

The characteristics of each of the five systems are defined in Table I. We denoted by AC-QoS and AC-IA the admission control mechanisms for QoS and interference avoidance, respectively. We also denoted by CA and RP the channel allocation, which can be either random (R) o with preference (P), and the repacking mechanisms.

TABLE I
Features of the systems studied.

System	SH	AC-QoS	CA	RP	AC-IA
1	N	N	R	N	N
2	Y	N/Y	R	N	N
3	N/Y	N	P	N	N
4	Y	N	P	Y	N
5	Y	Y	P	Y	Y

A. Evaluation of AC for QoS

We develop two analytical models to evaluate the performance of DSA systems from the QoS point of view. We denote by $\boldsymbol{x} = (x_1, x_2)$ the system state vector, when there are x_1 ongoing sessions of PU and x_2 of SU. 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

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

1) System 1: This first system is characterized by: not supporting SH, deploying a *Complete Sharing* admission policy, i.e. all SU requests are accepted while free resources are available, and deploying a random channel allocation (RCA) policy with no repacking.

A PU arrival in state $\boldsymbol{x}$ will force the termination of k SU, $k = 0, \ldots, \min(x_2, N)$, 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 SU are in the sub-bands occupied by the newly arrived PU session, while the other $(x_2 - k)$ are distributed in the other $(M - x_1 - 1)N$ 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 SU 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 SU, i.e. the successful completion rate of SU is determined by

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

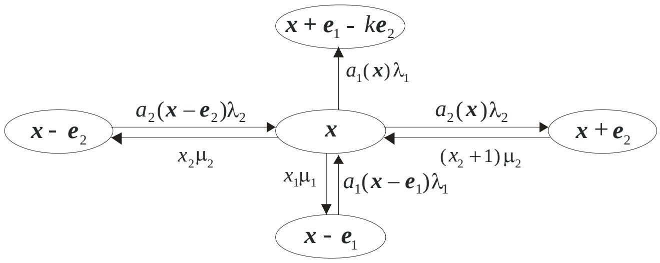

Fig. 1. State transition rates of the CTMC, $\boldsymbol{x} \in \mathcal{S}$.

2) System 2: This system is characterized by: supporting SH, deploying a *Fractional Guard Channel* admission policy and deploying a RCA policy with no repacking.

It is usually accepted that it is more disturbing for a subscriber to have an ongoing session dropped than the blocking of a new session setup. Then, to guarantee a certain degree of QoS to the SU, 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:

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

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 SU is t. Clearly, these resources are reserved for SU performing SH. 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 PU are unaffected by the admission policy, as SU are transparent to them.

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

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

Note that $k(\boldsymbol{x}) = 0$ when $C - b(\boldsymbol{x}) > N$, 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

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

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

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

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

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 $\pi(\boldsymbol{x})$ can be obtained, and from them the blocking probability for SU requests P_2, their forced termination probability P_2^{ft} and the SU throughput Th_2 can be determined using (2), (3) and (4).

To validate the analytical models we designed simulation models that mimic the behavior of the physical system and are therefore independent of the CTMC models.

B. Evaluation of Channel Allocation Mechanisms for Interference Avoidance

We assume that the *spectrum handover rate* induced by the arrival of new PU sessions is a measure of the interference caused by SU to the operation of PU, and we pursue to determine its value when deploying the spectrum access and channel repacking algorithms described in Section I. Besides, we compare these values to the ones obtained when deploying the conventional RCA scheme.

We first study a system in which no channel repacking is deployed. To evaluate the performance of the scheme we model the system as a CTMC. In a second study, we complement the CTMC model by incorporating channel repacking. As described later, the size of the CTMC grows very quickly with the total number of system channels. Therefore, for practical scenarios we resort to simulation.

It should be noted that the case in which repacking of PU is also performed is not considered. Deploying repacking of PU would only affect the algorithm followed to find free channels upon arrival of a SU but not to the system performance. Note that from the point of view of the performance perceived by SU when SH is supported, the channel allocation and repacking algorithms are irrelevant, i.e. the blocking and forced termination probabilities perceived by SU are the same.

Conversely, the interference perceived by PU is clearly affected by the the channel allocation and repacking algorithms. Lets denote by γ^{sh} and γ^{r} the rates of SH and repacking. Lets also denote by $CAPR$ the system in which CAP with repacking is deployed. Then, the following relations can be established,

$$\gamma^{sh}(RAC) > \gamma^{sh}(CAP) > \gamma^{sh}(CAPR) = 0$$
$$0 = \gamma^{r}(RAC) = \gamma^{r}(CAP) < \gamma^{r}(CAPR) \ .$$

1) System 3: This system is characterized by: supporting SH, deploying a *Complete Sharing* admission policy, deploying CAP and no repacking.

For the type of system under study, the state space of its CTMC model grows very quickly with the total number of system channels, as the state representation must describe not only the number of PU and SU ongoing sessions, but also the physical disposition of the allocated channels. More specifically, the number of states is $(N+2)^M$. This makes the solution of the CTMC intractable for any practical scenario. Instead, we developed a simulation model and validated it with the analytical model of a simple scenario with a total of $M = 2$ bands for PU and $M \times N$ sub-bands for SU. The set of feasible states for the process is

$$\mathcal{S} := \{\boldsymbol{y} = (y_1, y_2) : y_1, y_2 \in \{P, 0, \ldots, N\}\}$$

where y_1 (y_2) describes the state of the N leftmost (rightmost) channels. When $y_i = 0$ the band is empty, when $y_i = P$ it is occupied by a PU, otherwise the number of SU in the band can be $y_i = 1, \ldots, N$. Note that, for example, at state $(1, P)$ the actual channel allocated to the SU cannot be determined, but this is irrelevant for the performance parameters of interest. For $N = 2$, the system has 16 states, both when SH is supported and when it is not. By solving the balance equations together with the normalization condition the stationary distribution $\{\pi(\boldsymbol{y})\}$ can be obtained.

As an example, for a system where the SU support SH, the SH rate γ^{sh} and the forced termination rate γ^{ft} can be determined by

$$\gamma^{sh} = \lambda_1 \sum_{j=0}^{N} \sum_{i=0}^{N-j} i\pi(i,j)$$
$$\gamma^{ft} = \lambda_1 \Big[\sum_{i=0}^{N} \sum_{j=0}^{i} j\pi(i, N-i+j) + \sum_{j=0}^{N} j\pi(P,j) + \sum_{i=0}^{N} i\pi(i,P) \Big]$$

To compare the results of analytical and simulation models we selected three parameters: the blocking probability of PU and SU and the forced termination probability of SU. The parameters of the system configuration studied are: $M = 2$, $N = 2$, $\lambda_1 = 1$, $\lambda_2 = 1$, $\mu_1 = 1$, $\mu_2 = 1$. For the simulation models we defining a confidence interval of 95% and each result represents the average of 15 different simulation runs initialized with different seeds. For both systems, with and without SH support, the confidence interval diameters were smaller than $7 \cdot 10^{-5}$ and the absolute value of the relative errors with the analytical model were lower than $1 \cdot 10^{-3}$. These results clearly indicate a close agreement between results of analytical and simulation models.

2) System 4: This system is characterized by: supporting SH, deploying a *Complete Sharing* admission policy, deploying CAP and repacking.

If the system supports repacking, we would assume that it also supports SH. Clearly, repacking can be triggered when either a PU or a SU leave the system. Using the notation defined in previous section for a system with $M = N = 2$, repacking would take place, for example, when a SU leaves and the system state changes from $(1, 2)$ to $(1, 1)$. At this point, it is more convenient to move the SU in the lower band to the empty channel in the upper band, avoiding in this way future interference if a PU would arrive. Then, when repacking

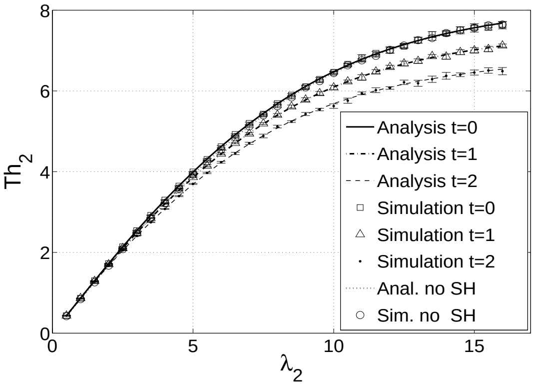

Fig. 2. $M = 3$, $N = 6$, $\lambda_b = 0.08$, $\mu_a = 0.82$ and $\mu_b = 0.06$.

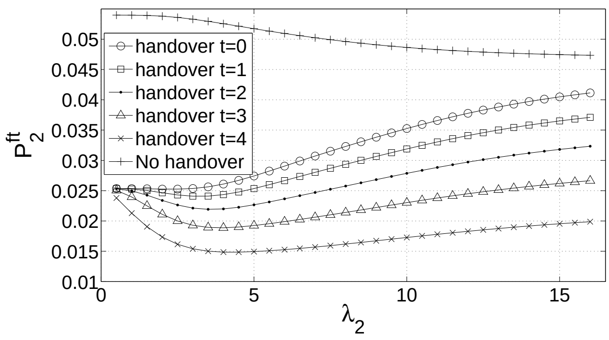

Fig. 3. Forced termination with the arrival rate of secondary users.

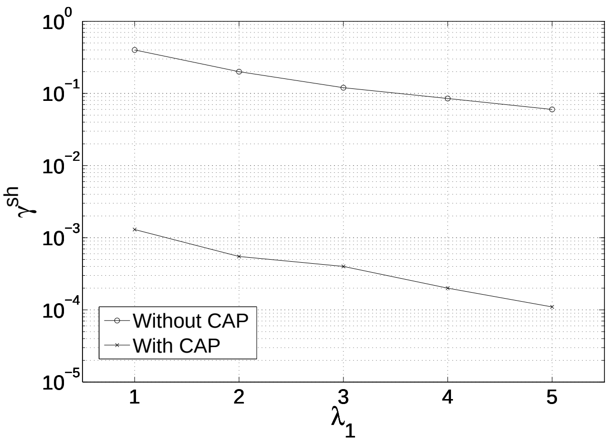

Fig. 4. Spectrum handover rate with the arrival rate of primary users.

takes place, the system moves from state $(1, 1)$ to state $(0, 2)$ automatically and in zero seconds.

As in previous section, we evaluate the system by simulation and validate the simulation model by a simple analytical model. For $M = N = 2$, the analytical model has 12 states, clearly less than in a system without repacking as now some states are not reachable, as shown in previous example. By solving the balance equations together with the normalization condition the stationary distribution $\{\pi(y_1, y_2)\}$ can be obtained.

To compare the results of the analytical and simulation models we selected the same parameters of merit and the same values for the configuration parameters as in previous section. Here the confidence interval diameters were smaller than $5 \cdot 10^{-5}$ and the absolute value of the relative errors with the analytical model were lower than $6 \cdot 10^{-4}$. Again, these results clearly indicate an excellent agreement between results of analytical and simulation models.

III. Numerical Evaluation

In this section we evaluate the effectiveness of incorporating the Fractional Guard Channel admission policy to limit the P_2^{ft}, as well as the effectiveness of incorporating the CAP algorithm to limit the interference induced by the SU on the PU.

A. *Effectiveness of the AC to limit the* P_2^{ft}

The results for the throughput of secondary users are shown in Fig. 2. Note the excellent agreement between the analytical and simulation models in Fig. 2, where the confidence intervals for a confidence level of 95% are shown for the simulation results. 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 SU 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 $t = 0$ (in Fig. 2 this curve is slightly above the one for a system with no handover). We believe that the role of reservation in cognitive radio systems might be the same as their classical role in cellular systems, i.e. to limit the forced termination probability of secondary users.

One the most interesting results of the DSA system studied is the evolution of the forced termination with the arrival rate of SU shown in Fig. 3. Observe that it seems to have a counterintuitive behavior. Intuitively, one would expect that the forced termination would increase with the arrival rate of SU. However in a system without SH 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. As in the scenario of Fig. 3 the arrival rate of PU is constant, then P_2^{ft} depends only on the ratio of forced terminations to accepted sessions. By comparing the evolution of the forced termination rate with the acceptance rate of SU for the interval of arrival rates of interest, these phenomena can be easily explained.

Clearly, the P_2^{ft} can be controlled by adapting the threshold t according to the traffic load of the system.

B. *Effectiveness of the CAP limit the* γ^{sh}

To evaluate the effectiveness of the CAP mechanism we define a system with the following parameters: $M = 2$, $N = 2$, $\lambda_2 = 1$ and $\mu_1 = \mu_2 = 1$. The results are shown in Fig. 4. Clearly, the mechanism is quite effective as it reduces the SH rate induced by the arrival of PU in two orders of magnitude.

IV. Adaptive Admission Control Scheme

In this section we propose an adaptive admission control scheme that is able to limit simultaneously both a measure of the forced termination probability (P_2^{ft}) and a measure of the interference caused by the operation of SU upon the PU communications.

We define the *reduced forced termination fraction* as $F^{ft} = \gamma^{ftr}/\lambda_2 (1 - P_2)$, where γ^{ftr} is number of times per time unit that the arrival of a PU induces the forced termination of at least one SU. We call γ^{ftr} the *reduced forced termination rate*, as it is smaller than the actual forced termination rate.

We define the *reduced interference fraction* F^{if}, as the fraction of PU arrivals that induce one or more SH. It can be determined as $F^{if} = \gamma^{shr}/\lambda_1$, where γ^{shr} is number of times per time unit that, upon arrival, a PU finds one or more SU occupying the band allocated to it. We call γ^{shr} the *reduced SH rate*, as it is smaller than the actual SH rate. Clearly, $F^{it*} = \gamma^{sh}/\lambda_1$, gives a more precise measure of the interference than F^{it}, as it takes into account all SH handovers induced by the arrival of PU.

Our scheme generalizes a novel adaptive AC strategy introduced in [15], which operates in coordination with the well-known trunk reservation policy named multiple guard channel (MGC). However, one of the novelties of the new proposal is that the adaptive scheme is now able to control simultaneously two objectives for the same arrival flow, i.e. the SU arrivals, as opposed to only one objective in the proposal described in [15]. The definition of the MGC policy is as follows. One threshold parameter is associated with each objective, $t^{ft}, t^{if} \in \mathbb{N}$. A SU arrival in state $\boldsymbol{x}$ is accepted if $b(\boldsymbol{x}) + b_2 \leq t$, $t = min\{t^{ft}, t^{if}\}$, and blocked otherwise. Therefore, t is the amount of resources that SU have access to and increasing (decreasing) it augments (reduces) the acceptance rate of SU request, which will in turn increase (decrease) both F^{ft} and F^{if}.

For the sake of clarity, the operation of our scheme is described assuming that arrival processes are stationary and the system is in steady state. We denote by F^{ft} the actual *reduced forced termination probability* perceived by SU and by B^{ft} its objective. In practice, we can assume without loss of generality that B^{ft} can be expressed as a fraction n/d, $n, d \in \mathbb{N}$. When $F^{ft} = B^{ft}$, it is expected that, in average, n *reduced forced termination* events and $(d - n)$ completed SU sessions events, will occur out of d accepted SU sessions events. For example, if the objective is $B^{ft} = 1/100$, then $n = 1$ and $d = 100$. It seems intuitive to think that the adaptive AC-QoS scheme should not change t^{ft} when the system is meeting its QoS objective and, on the contrary, adjust it on the required direction if the perceived QoS (F^{ft}) is different from the objective. Similar arguments can be used to describe the rational of the AC-IF scheme.

Given that the MGC policy deploys integer values for its threshold parameters, to limit F^{ft} below an objective $B^{ft} = n^{ft}/d^{ft}$ we propose to perform a probabilistic adjustment in the following way:

1: D, D^{ft} and D^{if} are internal flags.
2: Execute every SU arrival:
3: if $x_1 N + x_2 < C$: (free resources available)
4: if $b(\boldsymbol{x}) + b_2 \leq t^{ft}$ then $D^{ft} = 1$
else $D^{ft} = 0$
5: if $b(\boldsymbol{x}) + b_2 \leq t^{if}$ then $D^{if} = 1$
else $D^{if} = 0$
6: $D = D^{ft} \& D^{if}$
7: if $D = 1$ then "accept SU request"
else "reject SU request"
8: else "reject SU request"

Fig. 5. Admission control scheme for SU.

- At the arrival of a PU, if it forces the termination of a SU, do $\{t^{ft} \leftarrow t^{ft} - \Delta t^{ft}\}$ with probability $1/n^{ft}$.
- At the completion of a SU session, do $\{t^{ft} \leftarrow t^{ft} + \Delta t^{ft}\}$ with probability $1/\left(d^{ft} - n^{ft}\right)$, where $\Delta t^{ft} \in \mathbb{N}$ is the adjustment step for t^{ft}. Note that on average, $\left(d^{ft} - n^{ft}\right)$ are the number of completed SU sessions every d^{ft} accepted ones.

Under stationary traffic, if $F^{ft} = B^{ft}$ then, on average, t^{ft} is increased by Δt^{ft} and decreased by Δt^{ft} every d^{ft} accepted requests, i.e. its mean value is kept constant.

To limit F^{if} below an objective $B^{if} = n^{if}/d^{if}$, at the arrival of a PU:

- If it forces the execution of a SH, do $\{t^{if} \leftarrow t^{if} - \Delta t^{if}\}$, with probability $1/n^{if}$.
- If it does not force the execution of a SH, do $\{t^{if} \leftarrow t^{if} + \Delta t^{if}\}$, with probability $1/\left(d^{if} - n^{if}\right)$, where $\Delta t^{if} \in \mathbb{N}$ is the adjustment step for t^{if}.

Again, under stationary traffic, if $F^{if} = B^{if}$ then, on average, t^{if} is increased by Δt^{if} and decreased by Δt^{if} every d^{if} offered PU requests, i.e. its mean value is kept constant.

Note that in the AC-IA scheme we take into account SH induced by the arrival of a PU, those that successfully find a new channel to continue their communication and those forced to terminate. Clearly, F^{ft} and F^{if} are different from P_2^{ft} and F^{it*}, but we assume that the second ones can be limited by limiting the first ones.

When the traffic is non-stationary, the adaptive scheme will continuously adjust the thresholds in order to meet the objectives if possible, adapting to any mix of traffic. Note also that in the operation of this simple scheme no assumptions have been made concerning the arrival processes or the distribution of the session duration and cell residence times.

A. Numerical Results

The adaptive scheme has been evaluated in a scenario with the following parameters: $N = 2$, $M = 5$, $C = M \times M = 10$, $\lambda_1 = 2.5$, $\mu_1 = \mu_2 = 3$, $P_1 = 0.002$.

In Table II we show the results for a system in which the objective for F^{if} is more restrictive than the objective for F^{ft}. This can be clearly observed by the values of thresholds, where $E[t^{if}]$ is much lower that $E[t^{ft}]$. Note also that in the Table we show results for F^{if}, F^{if*} and P_2^{ft} and that the objectives

TABLE II
$B^{ft} = 0.05, B^{if} = 0.1, \Delta t^{ft} = \Delta t^{if} = 1.$

λ_2	F^{if}	F^{if*}	P_2^{ft}	$E[t^{if}]$	$E[t^{ft}]$
10	0.0978	0.1279	0.0164	9.6089	27240.87
15	0.1019	0.1298	0.0141	6.7813	24622.84
20	0.1003	0.1238	0.0128	6.3608	20820.98
25	0.0949	0.1148	0.0107	5.9909	17940.25
30	0.0968	0.1226	0.0112	5.8359	15751.02

TABLE III
$B^{ft} = 0.01, B^{if} = 0.1, \Delta t^{ft} = \Delta t^{if} = 1.$

λ_2	F^{if}	F^{if*}	P_2^{ft}	$E[t^{if}]$	$E[t^{ft}]$
10	0.0847	0.1026	0.0137	5467.71	9.0819
15	0.0872	0.1135	0.0136	494.37	6.8999
20	0.1020	0.1272	0.0104	6.4804	596.32
25	0.0955	0.1211	0.0108	6.0690	610.62
30	0.1023	0.1259	0.0098	5.9542	700.92

are defined by $B^{ft} = 0.005$ and $B^{if} = 0.1$. As observed, by limiting F^{if} we are also effectively limiting F^{if*}, although as expected $F^{if*} > F^{if}$. Finally, note that the P_2^{ft} values are much lower than the objective.

In Table III we show the results for a system in which the more restrictive objective changes with the SU load. For low load ($\lambda_2 < 20$), the objective for F^{ft} is more restrictive than the objective for F^{if}, as $E[t^{ft}]$ is much lower that $E[t^{if}]$. While for high load ($\lambda_2 \geq 20$), the objective for F^{if} is more restrictive than the objective for F^{ft}, as $E[t^{if}]$ is much lower that $E[t^{ft}]$. As observed, by limiting F^{ft} we are also effectively limiting P_2^{ft}, although as expected $P_2^{ft} > F^{ft}$.

Finally, in Table IV we show the results for a system in which the objective for F^{ft} is more restrictive than the objective for F^{if}. Similar comments to the ones made previously would also apply in this system.

V. Conclusions

We have studied a DSA system in which SU 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 SU and the interference produced on the PU by the operation of the SU. To meet these two objectives simultaneously, we first show that exerting admission control upon the SU as well as deploying common channel allocation and repacking algorithms are very effective mechanisms to achieve the goal.

Finally we proposed and evaluated a novel adaptive admission control scheme that is able to limit simultaneously the aforementioned objectives.

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TABLE IV
$B^{ft} = 0.005, B^{if} = 0.1, \Delta t^{ft} = \Delta t^{if} = 1.$

λ_2	F^{if}	F^{if*}	P_2^{ft}	$E[t^{if}]$	$E[t^{ft}]$
10	0.0327	0.0405	0.0066	15700.10	6.2378
15	0.0388	0.0396	0.0066	8565.77	5.6938
20	0.0271	0.0361	0.0056	6379.63	4.4659
25	0.0451	0.0584	0.0057	6090.78	5.2196
30	0.0465	0.0635	0.0061	4727.57	5.0304

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