Performance Analysis of Coordinated Cognitive Radio Networks under Fixed-Rate Traffic with Hard Delay Constraints

S. Lirio Castellanos-López, Felipe A. Cruz-Pérez, Mario E. Rivero-Ángeles, and Genaro Hernández-Valdez

Abstract: **Due to the unpredictable nature of channel availability, carrying delay-sensitive traffic in cognitive radio networks (CRNs) is very challenging. Spectrum leasing of radio resources has been proposed in the so called coordinated CRNs to improve the quality of service (QoS) experienced by secondary users (SUs). In this paper, the performance of coordinated CRNs under fixed-rate with hard-delay-constraints traffic is analyzed. For the adequate and fair performance comparison, call admission control strategies with fractional channel reservation to prioritize ongoing secondary calls over new ones are considered. Maximum Erlang capacity is obtained by optimizing the number of reserved channels. Numerical results reveal that system performance strongly depends on the value of the mean secondary service time relative to the mean primary service time. Additionally, numerical results show that, in CRNs without spectrum leasing, there exists a critical utilization factor of the primary resources from which it is not longer possible to guarantee the required QoS of SUs and, therefore, services with hard delay constraints cannot be even supported in CRNs. Thus, spectrum leasing can be essential for CRN operators to provide the QoS demanded by fixed-rate applications with hard delay constraints. Finally, the cost per capacity Erlang as function of both the utilization factor of the primary resources and the maximum allowed number of simultaneously rented channels is evaluated.**

Index Terms: **Call admission control, coordinated cognitive radio networks, Erlang capacity, new call blocking and call forced termination probabilities, QoS, spectrum leasing, stringent delay sensitive traffic.**

I. INTRODUCTION

In cognitive radio networks (CRNs), the licensed or primary users (PUs) take precedence over unlicensed or secondary users (SUs) to utilize the licensed spectrum band [1], [2]. That is, if a PU wants to access a frequency band and finds one or more SUs using the same band, transmissions of those SUs will be interrupted. These prematurely terminated secondary sessions degrade quality of service (QoS) and network throughput. Thus, supporting QoS in CRNs is a challenge due to the unpredictable nature of channel availability [3]. In this respect, call admission control (CAC) is critical for supporting QoS in CRNs [3]–[5]. In relation to the CAC issue, authors in [4] demonstrated that the optimal admission control policy in CRNs with spectrum overlay sharing depends only on the total number of users (i.e., it does not depend on the number of PUs and SUs in the system individually) in the network and it is of threshold type. Admission control is often jointly considered with other mechanisms employed to reduce service interruption and/or to provide QoS provisioning in CRNs [3]–[5]. Among the most relevant of these mechanisms are spectrum handoff, call buffering, preemptive priority, channel reservation, spectrum adaptation, and spectrum leasing [6]–[8]. In this research direction, there is a recently growing interest in (dynamic) spectrum leasing [8]–[16]. Spectrum leasing is a mechanism proposed in the so-called *coordinated cognitive radio networks* (CCRNs) to guarantee QoS of secondary traffic [8]. In CCRNs, the total spectrum-band is divided into *normal spectrum-band*, in which PUs can preempt SUs, and *leased spectrum-band* reserved for exclusive use of the secondary network. In other words, with dynamic spectrum leasing, a spectrum owner rents to the secondary network part of its spectrum in exchange of some incentive (e.g., monetary rewards as leasing payments) [10]. The cost of temporarily leasing a spectrum band is generally higher than the cost of sensing for white spaces in the normal spectrum-band. Nonetheless, as it is shown in this work, spectrum leasing is essential to guarantee suitable QoS in CRNs, especially in those networks offering stringent delay-sensitive services. This paper focuses on overlay spectrum sharing among infrastructure-based CRNs with and without spectrum leasing [2]. Specifically, in this paper, the performance of CCRNs under fixed-rate with hard-delay-constraints (FR-HDC) type of traffic is investigated. To this end, a session-level teletraffic model for the performance evaluation of CCRNs considering that both blocked sessions and interrupted sessions are clear from the system is developed. That is, a secondary type of traffic that has the most stringent QoS requirements (such as the unsolicited grant service class in mobile WiMAX [32]) is considered. For the adequate and fair performance comparison, call admission control strategies with fractional channel reservation to prioritize ongoing secondary calls over new ones are considered as in [17] and [20]. In order to obtain an upper bound on the performance of CCRNs with FR-HDC traffic, our proposed analytical model assumes that the

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rented spectrum is available as required by the secondary network, that is, the specific procedure used by the CRN to acquire (rent) spectrum is not considered. Considering spectrum leasing strategies that takes into account the dynamic traffic load of rented resources and secondary users is out of the scope of this paper and it represents a topic of our current research; nevertheless, a discussion on these issues is provided at the last paragraph of Section II. (For readers interested in paradigms for dynamic spectrum leasing, please refer to [8]–[16], [25].) Building on our developed teletraffic model, mathematical expressions for the new call blocking, interruption, and forced termination probabilities are obtained. In addition, for a given QoS requirement at session level (i.e., session blocking and forced termination probabilities) and maximum allowable number of simultaneously rented channels, the maximum Erlang capacity is computed. Furthermore, the impact of the relative value of the mean service time of SUs to the mean service time value of PUs on system performance is investigated. To the best of the authors' knowledge, this dependence of the performance of CRNs on the mean service times has not been previously reported in the literature. Also, the impact of resource leasing and channel reservation on the Erlang capacity of a CCRN with FR-HDC traffic is studied. In this respect, the fraction of time during which the secondary network uses leased radio resources is calculated. This quantity is used to estimate the economical cost of spectrum leasing per capacity Erlang. Numerical results provide new and important insights into the performance behavior of CCRNs under FR-HDC traffic as it is shown in Section IV of this paper.

A. Related Work

The merit of this section is to summarize the previously published studies that have addressed the performance of cognitive radio networks with FR-HDC traffic.

Authors in [17] analyzed the fractional guard channel reservation scheme to limit the forced termination probability of SUs in a CRN in which the spectrum handover technique is employed. In a related work [3], the optimal admission control and channel allocation decisions in cognitive overlay networks to support delay sensitive communications of unlicensed users are derived. Authors in [4] demonstrated that the optimal admission control policy in CRNs with spectrum overlay sharing depends only on the total number of users (i.e., it does not depend on the number of PUs and SUs in the system individually) in the system and it is of threshold type. On the other hand, in [13], considering multiple classes of SUs, a heterogeneous-prioritized spectrum sharing policy for coordinated dynamic spectrum access networks is proposed. Additionally, authors in [13] develop two CAC strategies based on the channel reservation concept to enhance the maximum admitted traffic of SUs for the system. One of the proposed CAC strategies in [13] reserves channels (i.e., Guard Channels -GCs-) only for use of PUs and the rest of channels (i.e., Shared Channels -GC-) are shared by all users (both PUs and SUs). In this strategy, a restrict function is used to balance the resource allocation between the different types of SUs. In the other CAC strategy proposed in [13], considering two types of SUs, the channels are divided into three groups: GCs, SCs, and restricted channels (RCs). RCs are reserved for the exclusive use of one type of SUs and cannot be used by the other type of SUs. Contrary to the work developed in [3]–[4], [13], and [17], in this paper spectrum leasing and reservation of channels for exclusive use of SUs are considered. Also, the factors that impact on the Erlang capacity of the system are investigated.

Authors in [8], proposed a spectrum sharing scheme in which the dynamic spectrum access among PUs and SUs is coordinated by dividing the spectrum into the normal access channels (that may be taken back anytime by PUs) and the reserved secondary channel (that are locked by occupied SUs until call sessions are complete). However, in [8] neither CAC strategy to prioritize ongoing secondary calls over the new ones nor Erlang capacity maximization is considered. Contrary to [8], in this paper both the critical utilization factor of the primary resources and the impact of the number of rented resources on the spectrum leasing cost are investigated. Finally, in an early work [18], we study the Erlang capacity in CCRNs with delay-sensitive traffic. However, in [18], the impact of the mean service time of SUs on system performance is not addressed. Specifically, in this work, we additionally investigate the effect of both the absolute and relative value of the secondary mean service time on new call blocking probability, forced termination probability and maximum Erlang capacity.

The rest of this paper is structured as follows. System model and general assumptions are given in Section II. Our proposed mathematical model for delay-sensitive traffic over CCRNs with spectrum leasing and fractional channel reservation is developed in Section III. Numerical results are analyzed in Section IV, before concluding remarks are exposed in Section V.

II. SYSTEM MODEL

The connection level analysis developed in Section III captures relevant aspects of delay-sensitive traffic over cognitive radio networks with spectrum leasing. These aspects and assumptions are presented in this section. It is important to remark that we adopt the system model proposed in [8].

A. Coordinated Cognitive Radio Network Model

The CCRN consists of two coordinated wireless networks operating in a given service area. The one that owns the license of the spectrum is referred to as the primary system (PS). The other network in the same service area is referred to as the secondary system (SS), which opportunistically shares the spectrum resource with the PS, while causing negligible interference to the PUs [1]. Naturally, the CCRN requires each system to know a certain amount of information about the other system. However, it is desirable to minimize the awareness that the PS needs to have on the SS [9].

It is assumed that resources are rented to another operator and the rented spectrum is available as required by the secondary network. Similar assumption that rented spectrum is available as required by the secondary network has been previously considered in the literature (see references [7], [8], [29]–[31]). On the other hand, PUs are not aware of the existence of activities of SUs, and SUs can detect activities of PUs through spectrum sensing.

Referring to spectrum sensing, it is has been shown in the literature [5], [21]–[24] that the effect of false alarm and misdetection can be plugged with no major problem into most of the developed mathematical analysis of CRNs. However, in this paper, to keep our mathematical analysis simple, we assume ideal spectrum sensing (spectrum sensing is error free). This represents a reasonable assumption in CRNs where a sensor network having enough sensors performing collaborative sensing of the radio environment in space and time is employed as it is considered in [3] and [10]. Modeling of spectrum sensing error in cognitive radio networks has been addressed in [21]–[24] and [30]. Additionally, for the interested reader, the effect of unreliable spectrum sensing in CRNs under voice over Internet Protocol traffic is investigated in our early work [5]. Also as in [5], it is assumed that service events are unlikely to happen during the sensing period since the sensing periods are relatively small.

System performance at the downlink of a wireless CCRN is addressed, i.e., only the local domain at the receiving end is considered [19][1] . The arrival of both primary and secondary users is assumed to be independent Poisson processes with arrival rate $\lambda^{(P)}$ and $\lambda^{(S)}$, respectively. Service time of both primary and secondary users is assumed to be independent exponentially distributed with means $1/\mu^{(S)}$ and $1/\mu^{(P)}$, respectively.

We assume a single base station (i.e., evolved node B or eNB in LTE vocabulary) that performs transmission of secondary sessions over *M* normal primary channels and a maximum allowable number *R* of simultaneously rented sub-channels. Each normal primary channel consists of *N* sub-channels. We assume that $0 \leq R < NM$. We refer to a channel as a resource block in a LTE system. For simplicity sake, we consider a fair channel model in which all channels have the same data rate (it is left as a future work to develop a teletraffic model that captures the varying capacity/throughput per user, which is a common feature of modern packet based systems). Each normal or rented sub-channel can handle only one secondary session. Thus, the system can handle up to $MN + R$ simultaneous secondary sessions. In the sequel we define $S = MN + R$. Referring to the *MN* shared sub-channels, PUs always have a higher channel access priority over SUs. On the other hand, the rented sub-channels are used exclusively by SUs. As in [17], due to the fact that blocking ongoing secondary calls is more annoying that blocking new call arrivals, from the total number of sub-channels (i.e., *S*) a fractional number *r* of sub-channels (composed of rented and/or normal sub-channels) is reserved for exclusive use of interrupted secondary calls. Thus, *r* is real and $0 \leq r \leq S$[2]. Fig. 1 illustrates the schematic diagram of our proposed system/spectrum sharing model. In particular, Fig. 1 shows how the total spectrum band is allocated to primary calls and (ongoing and new) secondary calls. It is assumed that SUs requesting service are able to connect and stay connected up to the end of their sessions (if there are enough available resources to this end) to this base station; that is, no handoff mechanism is considered (typical in low mobility scenarios).

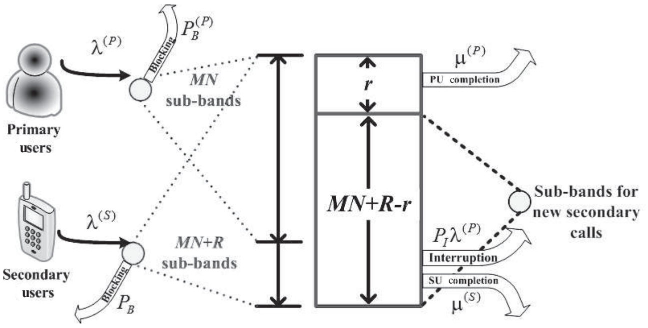

Fig. 1. System model for the coordinated cognitive radio network.

B. Call Admission Control Strategy

In the sequel, let us represent by k_0 and k_1 the total number of PUs and SUs in the system, respectively.

Taking into account that *r* is considered a fractional number, the proposed threshold-type call admission control strategy works as follows.

Upon the arrival of a new secondary call, if $k_0 N + k_1 < S - \lceil r \rceil$ (where '$\lceil \rceil$'is the ceiling operation) the new secondary arrival is accepted. Conversely, if $k_0 N + k_1 < S - \lceil r \rceil$ the new secondary arrival is rejected. On the other hand, when there are $k_0 N + k_1 < S - \lceil r \rceil$ total users in the system and a new secondary session arrives, it is blocked with probability $p = r - \lfloor r \rfloor$ and it is accepted with probability $(1 - p)$, where the symbol '$\lfloor \rfloor$' denotes the floor operation.

PUs have priority to acquire the normal sub-channels that are used by SUs at any time. Upon a PU service request arrival, it is accepted if $k_0 < M$, otherwise it is rejected. If the normal channel assigned to a new primary arrival is occupied by one or more secondary calls, all of these secondary calls must relinquish their transmission immediately. These preempted secondary sessions are switched to idle normal sub-channels, if they are available, to continue their calls (this process is called spectrum handoff). If no available normal sub-channels exist in the system, preempted secondary calls are switched to available rented sub-channels. If no enough rented sub-channels are available to carry all of the preempted secondary calls, then, some of these calls are forced to terminate.

It is considered that if an available normal sub-channel is detected and there exist secondary calls using rented sub-channels, one of those calls is swithced to the idle normal sub-channel. This procedure is useful when the dynamic spectrum leasing policy allows reducing the cost of leasing a spectrum band as the occupancy of rented sub-channels decreases.

It is worth noting that, some issues concerning the practical implementation of dynamic spectrum leasing strategies have to be considered as identified in [12] and [25]. For instance, whenever the SS identifies the need to lease some portion of spectrum, it sends a leasing petition with the number of channels

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[1] End-to-end QoS provisioning can be divided into two parts: QoS in the local (wireless) domain and QoS in the backbone domain. Since system impairments across the connection of the delay-sensitive application are cumulative, the required QoS at the local domain is determined by the QoS achieved at the backbone domain. After extraction of possible QoS values achieved at the backbone domain, the remaining QoS budget for the local domain is, in general, quite limited [19]

[2] The fractional channel reservation mechanism finely controls the communication service quality (in terms of new call blocking and forced termination probabilities) by varying the average number of reserved channels by a fraction of one. This allows the system (under a specific call admission control strategy) to reach its maximum capacity while meeting the quality of service constraints. In this manner, the performances of different call admission control strategies can be compared under a fair basis [17], [20], [26], [27]

required. The spectrum owner grants or rejects such request according to the current occupation in its network and sends a control packet indicating the grant or reject of the required bandwidth. In case that the spectrum owner accepts the spectrum leasing it has to inform the specific channels assigned and the time moment at which they are assigned. The SS has to inform the moment at which each of the leased channels are returned to the spectrum owner. Note that in this scenario, there are at least two time slots required if the processing time is neglected and if we consider that a time slot is sufficient to send the pertinent information regarding these procedures. Hence, a certain delay has to be considered from the moment that the leasing procedure begins until the instant that the resources are assigned in order to have realistic operation conditions. Also, due to the fact that rented spectrum could be not available as required by the secondary network[3] ; the SS may use different strategies to request the spectrum owner resources. For instance, the SS can request the leasing of spectrum from the spectrum owner when: a) The buffer occupancy is higher that a certain threshold; b) the packet loss probability is higher than a certain threshold. The rationale behind these strategies is that if the traffic load at the SS is detected to be increasing, it is highly possible that it continues to increase. As such, the networks should guarantee to have available resources (i.e., anticipated resource leasing) ready in case that they are required; in this manner the delay introduced by the real time leasing procedure is reduced. Another possible mechanism (that we call postponed resource releasing mechanism) to reduce the delay introduced by the real time leasing procedure is as follows. When a leased channel is released by a secondary session, it is not immediately returned to the spectrum owner. Instead this (just released) leased channel is retained by the SS by a certain amount of time in order to consider the possibility that a secondary session will require an available resource in the short term. The main drawback of anticipated resource leasing (postponed resource releasing) is that the leasing (releasing) is performed before the resources are required (after resources have been unused for a while) and there may be some resource wastage[4] . Due to the complexity of such schemes, dynamic spectrum leasing strategies that consider both anticipated resource leasing and delayed spectrum releasing to mitigate the effects of resource unavailability are left as a future research work.

III. CONNECTION-LEVEL ANALYSIS

In this section, a connection-level analytical model for the performance evaluation of CCRN with FR-HDC traffic is built and studied. The mathematical formulation presented in this section is based in well-known multidimensional birth and death processes that can be found in [28]. A two-dimensional birth and death process is used to obtain the probability distribution of primary and secondary users in the system; the corresponding state transition diagram is shown in Fig. 2. To capture the fact that the number of reserved sub-channels for interrupted secondary calls is assumed to be real, $\lfloor r \rfloor + 1$ sub-channels are reserved with probability $p = r - \lfloor r \rfloor$ and only $\lfloor r \rfloor$ sub-channels are reserved with probability $(1 - p)$. For the analyses developed in this paper, state variables are represented by the vector $\mathbf{k} = [k_0, k_1]$. Let us represent by $\mathbf{e}_i$ a unit vector of size 2 whose entry at the ith$(i = 0, 1)$ position is 1 and its entry at the other position is 0. The set of feasible states, Ω_0, can be built as follows

$$\Omega_0 = \{\mathbf{k} | 0 \le k_0 \le M \cap 0 \le k_1 \le S \cap 0 \le Nk_0 + k_1 \le S\}.$$

The system dynamics are triggered by the following events: PU request arrival, SU request arrival, SU departures, PU service completion. Thus, the *continuous-time Markov chain* (CTMC) showed in Fig. 2, is proposed to perform the analysis of the CCRN. In this analysis, it is considered that the CAC strategy accepts new secondary request arrivals if there are less than $S - r$ occupied resources in the system, where r is used to prioritize ongoing secondary calls over new secondary calls. Let us represent by $a_i(\mathbf{k})$ the transition rates in state $\mathbf{k} = [k_0, k_1]$ due to either a PU arrival $(i = 0)$ or a SU arrival $(i = 1)$. According to Fig. 2, these transition rates correspond to the following state transitions $\mathbf{k} - \mathbf{e}_i \to \mathbf{k} \to \mathbf{k} + \mathbf{e}_i$. On the other hand, let us represent by $b_i(\mathbf{k})$ the transition rates in state $\mathbf{k}$ due to either a PU service termination $(i = 0)$ or a SU departure $(i = 1)$. According to Fig. 2, these transition rates correspond to the following state transitions $\mathbf{k} + \mathbf{e}_i \to \mathbf{k} \to \mathbf{k} - \mathbf{e}_i$ (for $i = 0, 1$). Finally, the case where a primary user arrival entails service interruptions of j ongoing secondary calls (for $j = 1, 2, \cdots, N$) is represented by transition $c(\mathbf{k})$ and, as Fig. 2 shows, this transition rate corresponds to the following state transitions $\mathbf{k} - \mathbf{e}_0 + j\mathbf{e}_1 \to \mathbf{k} \to \mathbf{k} + \mathbf{e}_0 - j\mathbf{e}_1$.

According to the system model and the call admission control strategy described in Section II.B, it is straightforward to show that the transition rates $a_i(\mathbf{k})$, $b_i(\mathbf{k})$ and $c(\mathbf{k})$ can be computed as follows

$$a_i(\mathbf{k}) = \begin{cases} \lambda^{(P)}; & 0 \le k_0 < M, i = 0 \\ \lambda^{(S)}; & k_1 \ge 0; Nk_0 + k_1 < S - \lfloor r \rfloor - 1, i = 1 \\ (1-p)\lambda^{(S)}; & k_1 \ge 0; Nk_0 + k_1 = S - \lfloor r \rfloor - 1, i = 1 \\ 0; & \text{otherwise} \end{cases}$$

$$b_i(\mathbf{k}) = \begin{cases} k_0 \mu^{(P)}; & k_0 \le M, Nk_0 + k_1 \le S, i = 0 \\ k_1 \mu^{(S)}; & Nk_0 + k_1 \le S, i = 1 \\ 0; & \text{otherwise} \end{cases}$$

$$c(\mathbf{k}) = \begin{cases} \lambda^{(P)}; & 0 \le k_0 < M, 0 \le k_1 \le S \\ 0; & \text{otherwise} \end{cases} .$$

The transition rates are derived by going through all the possible sequences of valid states taking into account the call admission control strategy and assumptions described in Section II. The following illustrative example is provided:

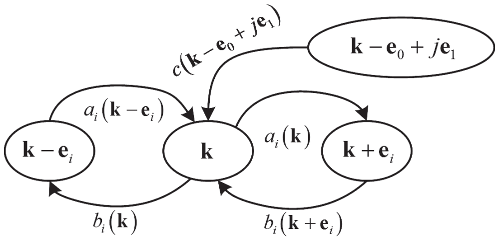

Fig. 2. State transitions diagram.

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[3] In [25], a given probability that the request for a new frequency band is successful is considered to model resource availability of rented resources.

[4] In [25], an operation rule based on a hysteresis control with two thresholds for the network operator to rent or give back frequency bands based on the offered traffic is proposed.

$$\begin{aligned} P(\mathbf{k})\sum_{i=0}^{1}(a_i(\mathbf{k})+b_i(\mathbf{k})) &= \sum_{i=0}^{1}a_i(\mathbf{k}-\mathbf{e}_i)P(\mathbf{k}-\mathbf{e}_i)+\sum_{i=0}^{1}b_i(\mathbf{k}-\mathbf{e}_i)P(\mathbf{k}-\mathbf{e}_i) \\ &+ \sum_{j=1,Nk_0+k_1=S}^{N} c(\mathbf{k}-\mathbf{e}_0+j\mathbf{e}_1)P(\mathbf{k}-\mathbf{e}_0+j\mathbf{e}_1) \end{aligned} \tag{1}$$

Consider the transition from state $\mathbf{k}-\mathbf{e}_0+j\mathbf{e}_1$ to state $\mathbf{k}$. This transition corresponds to the scenario whereby a new primary request arrives to the system and simultaneously founds A available normal channels (i.e., there are $M-A$ ongoing primary calls) and $k_1 = R+N(A-1)+j$ ongoing secondary sessions in the system, for $M \geq A \geq 1$ and $j = 1, 2, \cdots, N$. Notice that, under these conditions and after some possible successful spectrum handoffs (if required), a total number of j secondary sessions are forced to terminate.

Given feasible states and their transitions in the previously described CTMC, the global set of balance equations can be constructed as (1).

Based on these equations and the normalization equation, we can solve the set of the linear equations and consequently the state probabilities $P(\mathbf{k})$ of the Markov chain. Once the state probabilities $P(\mathbf{k})$ are obtained, the new call blocking, forced termination, and interruption probabilities of the secondary network can be obtained.

Blocking probability, P_B, is the sum of the probabilities of states that cannot accommodate more services of SUs. Thus, P_B can be expressed as follows.

$$\begin{aligned} P_B &= \sum_{\mathbf{k}\in\Omega_0|Nk_0+k_1=S-\lfloor r\rfloor-1} pP(\mathbf{k}) \\ &+ \sum_{\mathbf{k}\in\Omega_0|Nk_0+k_1>S-\lfloor r\rfloor-1} P(\mathbf{k}). \end{aligned} \tag{2}$$

Similarly, the probability P_I that an ongoing secondary call be interrupted due to the arrival of a primary call can be expressed as (3).

Forced termination probability (denoted by P_{ft}) represents a preemption of an ongoing secondary call due to the arrival of a PU. Then, the forced termination probability is the fraction of secondary calls that are forcedly terminated due to the arrival of PUs over the whole number of accepted new secondary arrivals. Thus, P_{ft} can be expressed as (4).

Finally, given the target values for the secondary blocking and forced termination probabilities and the maximum allowed number of rented channels, the optimal number r of reserved channels for spectrum handoff that maximizes the Erlang capacity (denoted by a) is obtained. The optimal value of r is found by using the well-known bisection algorithm [20]. The optimization procedure ends when the maximum value of the Erlang capacity is found. The capacity maximization procedure is based on the following observations: a) Blocking probability increases as the number r of reserved channels increases and b) forced termination probability decreases as the number r of reserved channels increases. Building on this, a two-loop optimization procedure is employed. First, an initial value of the secondary traffic load (denoted by a) to be tested as the Erlang system capacity is set. In the inner optimization loop, using the bisection algorithm, a value of the number r of reserved channel such that the value of forced termination probability equals its target value is found. In the outer optimization loop, if the value of new call blocking probability equals its target value with the found number of reserved channels in the inner optimization loop, the maximum Erlang capacity has been found. In the contrary case, a has to be either increased (if the new call blocking probability is smaller than its target value) or decreased (if the new call blocking probability is greater than its target value). The optimization procedure ends when the maximum value for a such that both blocking and forced termination probabilities equal their respective target values is found.

IV. NUMERICAL RESULTS

The goal of the numerical evaluations presented in this section is to study the impact of the mean service time of SUs, spectrum leasing, and channel reservation on the performance of CCRNs under fixed-rate with hard-delay-constraints (FR-HDC) traffic. In turn, this study allows us to verify the applicability as well as the preciseness and robustness of our mathematical model developed in Section III. System performance is evaluated in terms of new call blocking probability, forced termination probability, Erlang capacity, effective occupation probability of leasing resources, and cost per Erlang capacity. Unless otherwise specified, the following parameters are applicable (similar values were used in [8]): $\mu^{(S)} = 1.2$, $\mu^{(P)} = 0.8$ (that is, the relative mean service time of SUs defined as $\mu^{(P)}/\mu^{(S)}$ and denoted here after by T_r, is equal to 2/3); $M = 30$; $N = 1$. In addition, thresholds for secondary session blocking (P_{b_tr}) and forced terminate $(P_{\mathrm{ft\_tr}})$ probabilities are fixed to 2 % and 0.2 %, respectively. All the results of this section depict the performance of a CCRN with FR-HDC traffic.

To validate our teletrafic model developed in Section III, Figs. 3 and 4 present both analitical and simulation results for the new call blocking and forced termination probabilities, respectively. New call blocking and forced terminate probabilities are plotted as function of both the relative and the absolute values of the mean secondary service time for $R = 0$, $r = 0$, primary blocking probability of 0.5%, and a utilization factor of primary channels equals 0.63. New call blocking probability is analytically evaluated using (2), while forced termination probability is analytically evaluated using (4). Perfect agreement between

$$P_I = \frac{\displaystyle\sum_{\mathbf{k}\in\Omega_0 | Nk_0+k_1\geq S-N; k_1>0; k_0<M} \frac{(k_0+1)N+k_1-S}{k_1} P(\mathbf{k})}{\displaystyle\sum_{\mathbf{k}\in\Omega_0 | k_1>0} P(\mathbf{k})}. \tag{3}$$

$$P_{\text{ft}} = \frac{\displaystyle\sum_{\mathbf{k}\in\Omega_0 | Nk_0+k_1\geq S-N; k_1\leq S; k_0<M} ((k_0+1)N+k_1-S)\lambda^{(P)} P(\mathbf{k})}{\lambda^{(S)}(1-P_B)}. \tag{4}$$

analitical and simulation results are observed in Figs. 3 and 4.

On the other hand, Figs. 3 and 4, show the following relevant result. For a given value of the utilization factor of the primary channels, system performance does not depend on the absolute value of the mean secondary service time, instead it depends on the value of the mean secondary service time relative to the mean primary service time (i.e., T_r). In particular, Fig. 3 (Fig. 4) shows that new call blocking (forced termination) probability increases (decreases) as T_r decreases in detriment (benefit) of system performance (in terms of new call blocking and forced termination probabilities). Below, when Figs. 5 and 6 are analyzed, an explanation of this relevant behaviour is provieded. Then, it is imperative to have a proper characterization of the secondary service time to adequately planning, design, dimensioning, and optimizing cognitive radio networks under fixed-rate applications with hard delay constraints.

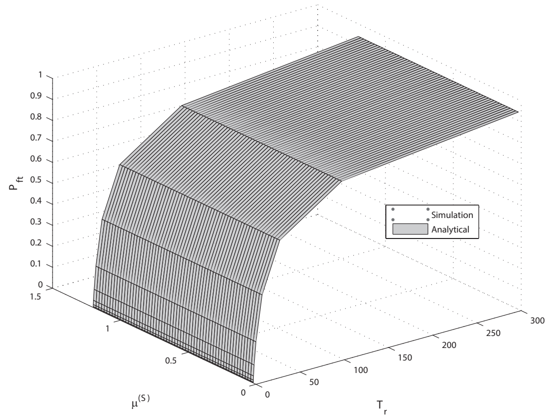


Fig. 4. Forced termination probability as function of both the relative and absolute values of the mean secondary service time.

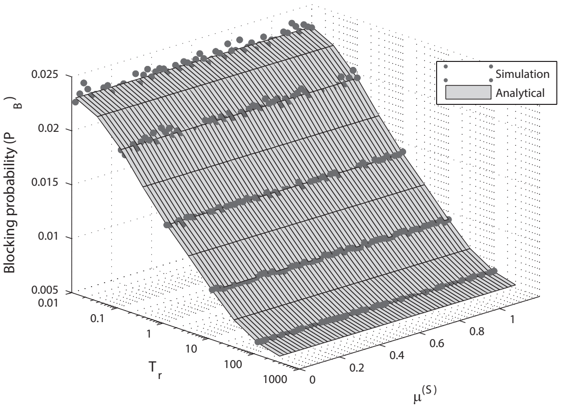


Fig. 3. Blocking probability as function of both the relative and absolute values of the mean secondary service time.

Fig. 5 depicts the maximum Erlang capacity as function of the utilization factor of the primary channels with the maximum allowable number of leased channels as parameter. The maximum Erlang capacity shown in Fig. 5 is obtained using the optimization procedure described in the last paragraph of Section III. Figs. 5(a), 5(b), and 5(c), consider that T_r is equal to 2/3, 2/30, and 20/3, respectively. As stated before, authors in [8] considered a fixed value of T_r equal to 2/3. In order to investigate the impact of T_r on the maximum Erlang capacity, we also consider in Fig. 5(b) and 5(c) a value of T_r one order of magnitude lower (higher) than the one employed in [8]. In Fig. 5, our proposed resource management strategy (labeled with “Proposed mode”) is compared against the one developed by Xu Mao *et al.* in [8] (denoted in all the figures of this section with the label “Xu Mao”). Some expected results can be extracted from Fig. 5. For instance, Fig. 5 shows that, irrespective of the value of T_r, Erlang capacity is a monotonically increasing (decreasing) function of the number of leased channels (utilization factor of primary channels). Also, Fig. 5 confirms that, irrespective of the value of T_r, Erlang capacity is a monotonically decreasing function of the utilization factor of primary channels.

Several important observations can be found in Fig. 5. Results presented in Figs. 5(a) and 5(b) indicate that, for scenarios where $R = 0$ (i.e., when no spectrum leasing is considered), Erlang capacity rapidly decreases as the utilization factor of the primary channels increases. In fact, Figs. 5(a) and 5(b) shows that for $R = 0$, there exists a critical utilization factor of the primary channels at which it is not longer possible to guarantee the QoS of the admitted secondary users (Erlang capacity abruptly decreases toward zero). For instance, Fig. 5(a) and 5(b) shows that this critical value is about 0.49 (0.573) for the strategy "$R = 0$ Xu Mao" and it is about 0.52 (0.625) for the strategy "$R = 0$ proposed model," that is, this critical point is increased about 6% (9%) by using our proposed strategy. In other words, these results reveal that, by using channel reservation for spectrum handoff, it is possible to extend the maximum arrival rate of PUs at which it is still possible to provide the QoS demanded by SUs. Also, Fig. 5 indicates that, as the utilization factor of the primary channels increases, a gradual reduction of the Erlang capacity is possible by using spectrum leasing (i.e., scenarios where $R > 0$). This is especially useful to increase user satisfaction in CRNs with delay-sensitive applications. In this sense, numerical results presented in Fig. 5 allow us to quantify the extent by which Erlang capacity is decreased due to the presence of PUs. For instance, Fig. 5(b) shows that, under the strategy "$R = 3$ proposed model" ("$R = 1$ proposed model"), as the utilization factor of the primary channels increases from 0.56 to 0.67, the Erlang capacity decreases from 6.8 (4.6) Erlangs to 3.17 (0.86) Erlangs, that is, Erlang capacity decreases 53% (81%). On the other hand, assuming the same scenario, Fig. 5 shows that our proposed strategies always outperform the corresponding strategies proposed by Xu Mao *et al.* in [8]. For instance, considering the case where the utilization factor of primary channels is equal to 0.6 and $R = 1$, Fig. 5(a) shows that our proposed strategy carries 112% more traffic that the "$R = 1$ Xu Mao" strategy. Again, this improvement is exclusively due to the use of channel reservation.

The most relevant result that can be extracted from Fig. 5 is perhaps the fact that system performance of CRNs with FR-HDC traffic is highly dependent on the mean service time of SUs relative to the mean service time of PUs (i.e., T_r). Specifically, Fig. 5 reveals that maximum Erlang capacity decreases as the value of T_r increases. To illustrate this, let us consider the strategy "$R = 3$ proposed model" for a utilization factor of 0.56. Under this scenario, the Erlang capacity increases from 3.8 Erlangs to 6.8 Erlangs as T_r moves from 2/3 (Fig. 5(a)) to 2/30 (Fig. 5(b)), that is, a capacity increase of 79% is observed. Also, for the same scenario, Erlang capacity decreases from 3.8 Erlangs to 1.13 Erlangs as T_r moves from 2/3 (Fig. 5(a)) to 20/3 (Fig. 5(c)), that is, a capacity decrease of 70% is observed. To remark this relevant result, Fig. 6 directly plots system Erlang capacity as function of T_r for a utilization factor of the primary channels equals 0.63. Fig. 6 clearly shows that Erlang capacity is a monotonically decreasing function of T_r. This behavior can be explained as follows. Notice that decreasing the value of T_r implies that the mean value of the secondary service time relative to the mean value of the primary service time decreases. Thus, as the relative value of the mean secondary service time decreases while the utilization factor of the primary channels remains unchanged, it is more probable to an ongoing secondary call to successfully terminate its service in benefit of both the interruption and forced termination probabilities. Also, as the relative value of the mean secondary service time decreases while the utilization factor of the primary channels remains unchanged, the departure rate of successfully terminated calls increases relative to the arrival rate of PUs; thus, the average number of available sub-channels increases in benefit of the new call blocking probability. The joint effect of these facts leads us to the behavior explained above and illustrated in Fig. 6.

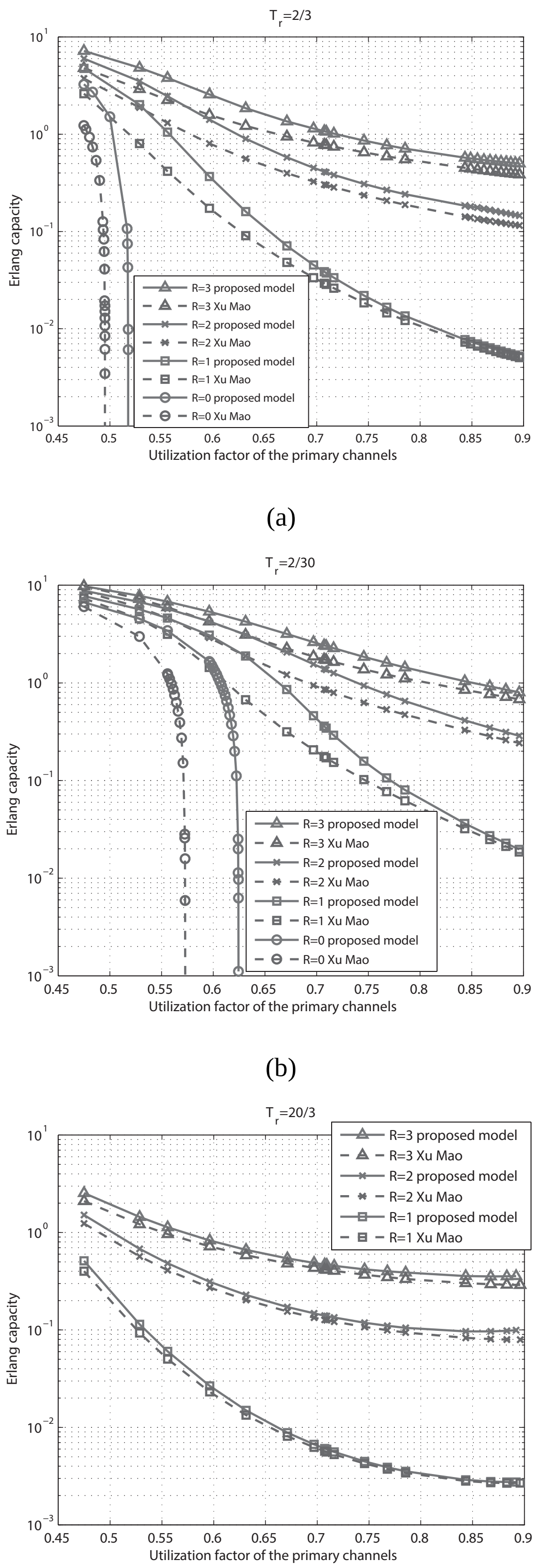
Table 1. Erlang capacity gain and optimal values of r as function of R for a CCRN with FR-HDC traffic.

Erlang capacity gain (%)relative to the when *R*=0	***R***	***r***
-	0	3.44
45.7	1	2.86
83.6	2	2.51
120.1	3	2.24

Table 1 presents the Erlang-capacity gain percentage respect to the case when no spectrum leasing mechanism is used (i.e., $R = 0$) in the CCRN with FR-HDC traffic. Table 1 also shows the most satisfactory values of the number of reserved channels for spectrum handoff (r) that maximize Erlang capacity (a). These values are obtained using the optimization procedure described in the last paragraph of Section III. Different values of the number of leased channels (R) are considered in Table 1. From Table 1, it is evident that spectrum leasing is an efective mechanism to strongly improve system Erlang capacity (and thus, QoS satisfaction) for CCRNs under fixed-rate services with hard delay constraints. For instance, by comparing the Erlang capacities respectively achieved by the CCRN with $R = 0$ and the CCRN with $R = 3$, it is observed that Erlang capacity improves 120% due to the use of spectrum leasing.

Table 2 presents the time proportion that the ith leased channel is used when the maximum allowable number of rented channels is $R (R \geq i)$. Two different primary traffic loads (high and low) are considered. The low (high) primary traffic load correspond to the case when the primary blocking probability $P_b^{(p)}$ is equal to 0.01% (10%). Let us consider, for instance, the case when the CCRN can rent up to two channels (say, channel 1 and channel 2) and a high primary traffic load is presented. Thus, the operator of the CCRN can have up two rented channels for exclusive use of SUs. From Table 2, it is observed that channel 1 (channel 2) is used only 15% (0.9%) of the time. This means that, the CCRN effectively uses, on average, only 0.159 additional (rented) channels. Therefore, with an ideal *dynamic spectrum leasing strategy*, the CCRN operator has to pay the rent of only 0.159 channels instead of 2 channels when *permanent spectrum leasing* is considered.

Table 3 presents the normalized cost per Erlang of supported capacity for both permanent spectrum leasing (PSL) and ideal dynamic spectrum leasing (ISL) strategies. Different primary traffic loads are considered with R as a parameter. Table 3 confirms that high reduction cost per rented channel can be achieved by the ISL strategy relative to the PSL one. Notice that reduction cost ranges from 70% to 99%. Thus, it is of paramount importance to develop dynamically spectrum leasing mechanisms that assist the CCRN operator to acquire radio resources only when those resources are needed [9]–[10]. This is a topic of our current research.



(a)

(b)

(c)

Fig. 5. Erlang capacity as function of the utilization factor of the primary channels with the maximum allowable number of rented channels as parameter for a relative mean service time of SUs equal to (a) 2/3, (b) 2/30, and (c) 20/3.

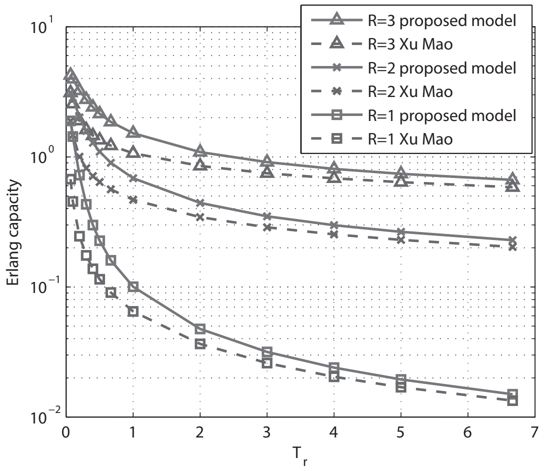


Fig. 6. Erlang capacity versus the relative mean secondary service time for a utilization factor of the primary channels equals 0.63.

Table 2. Time proportion that i rented channels are used when the maximum allowed number of rented channels is R. Both low and high primary traffic loads are considered.

R	$i = 1$	$i = 2$	$i = 3$	Effectively rented channels
Low primary traffic load (i.e.,$P_b^{(P)} = 0.01\%$)				
1	0.30	NA	NA	0.30
2	0.36	0.10	NA	0.47
3	0.49	0.17	0.05	0.71
High primary traffic load (i.e.,$P_b^{(P)} = 10\%$)				
1	0.007	NA	NA	0.007
2	0.150	0.009	NA	0.159
3	0.353	0.076	0.008	0.437

V. CONCLUSIONS

In this paper, the performance of CCRNs under fixed-rate with hard-delay-constraints traffic considering the use of spectrum leasing and fractional channel reservation for spectrum handoff was investigated and mathematically analyzed. In particular, mathematical expressions for new call blocking, interruption, and forced termination probabilities that capture relevant aspect of CCRN (i.e., preemption of ongoing secondary calls due to appearance of primary user arrivals, spectrum handoff, spectrum leasing mechanisms, threshold-based call admission control with fractional channel reservation strategies, among others) were derived. In addition, for given QoS requirements at the session-level and the total number of allowed rented channels, the maximum Erlang capacity as function of the occupancy factor of primary channels was evaluated. Also, the fraction of time that spectrum leasing is needed was calculated. This quantity was used to estimate the cost of spectrum leasing per Erlang. The study developed here provides relevant insights into the performance of CRNs under delay-sensitive traffic. For instance, numerical results clearly show that, for a given value of the utilization value of the primary channels, system perfor-

Table 3. Normalized cost per Erlang of supported capacity for both permanent and ideal dynamic spectrum leasing strategies. Different primary traffic loads are considered with R as a prameter.

R	Capacity (Erlang)	Cost with PSL	Cost with ISL	Maximun cost reduction relative to the PSL strategy (%)
Low primary traffic load (i.e.,$P_b^{(P)} = 0.01\%$)				
0	3.267	0	0	0
1	4.760	0.210	0.062	70
2	5.997	0.333	.078	77
3	7.191	0.417	0.099	76
$P_b^{(P)} = 0.50\%$				
0	0	0	0	0
1	0.160	6.247	0.597	90
2	0.898	2.226	0.448	80
3	1.855	1.617	0.365	77
$P_b^{(P)} = 1\%$				
0	0	0	0	0
1	0.071	14.079	0.729	95
2	0.579	3.452	0.567	84
3	1.355	2.214	0.468	79
High primary traffic load (i.e., $P_b^{(P)} = 10\%$)				
0	0	0	0	0
1	0.008	129.634	0.950	99
2	0.184	10.858	0.862	92
3	0.574	5.223	0.760	85

mance does not depend on the absolute value of the mean secondary service time, instead it depends on its relative value (respect to the mean primary service time). Numerical results also show that, in CRNs without spectrum leasing, there exists a critical utilization factor of the primary resources from which it is not longer possible to guarantee the required QoS of SUs and, therefore, delay-sensitive services cannot be even supported in CRNs. In addition, numerical results demonstrate that resource leasing and channel reservation are effective mechanisms to improve system capacity (and, thus, QoS) for fixed-rate applications with hard delay constraints over CCRNs. It is important to point out that, to our knowledge, most of the results and observation presented in this work have not been reported in the existing literature. Although these results were extracted for particular scenarios, with a certain set of parameter values, our contribution clearly shows that there are relevant aspects that have to be considered to adequately planning, designing, dimensioning, and optimizing cognitive radio networks under fixed-rate traffic with the most stringent QoS requirements.

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