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Operating point selection for primary and secondary users in cognitive radio networks

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ABSTRACT

This paper addresses the problem of opportunistic access of secondary users to licensed spectrum in cognitive radio networks. In order to avoid interference to the licensed primary users, efficient spectrum detection methods need to be developed. For this purpose, in recent years several sensing techniques have been proposed to monitor and regulate the spectrum access to the shared spectrum resources. However, spectrum sensing may be affected by errors in the form of missed-detections (i.e., an occupied spectrum is erroneously detected as free) or false-alarms (i.e., a free spectrum is erroneously detected as occupied). These two magnitudes pose a tradeoff on the design of the spectrum sensing mechanisms meaning that low missed-detection can only be achieved at the expense of high false-alarm and vice versa. Thus, the network designers should adaptively tune the sensing techniques such that the highest perceived Quality of Service (QoS) is achieved by both primary and secondary users. In this paper, a framework is introduced for determining the sensing operating points. Also the definition of Grade-of-Service (GoS) metrics is adopted to the case of primary/secondary users spectrum sharing. It is shown that the operating points of the sensing mechanisms can be easily adjusted according to the current traffic load of both primary and secondary users so that the perceived GoS is maximized. In addition, the Erlang Capacity of the spectrum sharing system for both primary and secondary users is also evaluated considering the effects of erroneous sensing.

1. Introduction

The spectrum efficiency and utmost usage in cognitive radio networks (CRNs) [1,2] calls for the implementation of advanced spectrum management mechanisms algorithms and architectures devoted to guarantee a non-interfering access to shared spectrum resources. The Hierarchical Access Model [3] refers to the problem where some licensed spectrum is *opened* for secondary usage on a non-harmful basis. In these scenarios, the discovery of spectrum opportunities for subsequent spectrum access becomes the key element enabling Opportunistic Spectrum Access (OSA) [3].

The considered deployment case in this work is that of an infrastructure-based system, e.g., traditional cellular networks. The Primary Network (PN) is intended to serve Primary Users (PUs) along with an infrastructure-based Secondary Network (SN) devoted to serve Secondary Users (SUs). The spectrum over which the PN operates, i.e., the licensed spectrum, is opened for secondary spectrum usage by the SN as long as SUs do not interfere with ongoing or newly arriving PU transmissions. Thus, the primary spectrum usage awareness at the SN is vital for a non-harmful operation. Several alternatives concerning spectrum awareness are envisaged which may include coordinated and uncoordinated operation between the PNs and the

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SNs. For the coordinated case, see e.g. [4–7], there is an explicit communication and synchronization between the PN and the SN which enables the SN to be aware of primary spectrum activity by means of dedicated channels. As for the uncoordinated case, the primary activity is essentially *invisible* to the SN and thus spectrum sensing mechanisms have to be implemented on the secondary side [8–11]. In this work, the focus will be on the uncoordinated case, i.e. the sensing-based case.

1.1. Motivation

Sensing-based spectrum discovery mechanisms, [12], may be affected by errors and, consequently, provide false information to the SU about PU spectrum occupancy. These errors are typically in the form of false-alarm (i.e., a free channel is erroneously sensed to be occupied) and misdetection (i.e., an occupied channel is erroneously sensed to be free). As explained hereafter, by adequately choosing the operating points of the sensing mechanisms, a tradeoff may be achieved between these two errors. As shown in the following, this means that low misdetection is attained at the cost of increased false-alarm and, conversely, low false-alarm is achieved at the cost of high missed-detection.

According to the above, the missed-detection error will mainly affect the interference of PUs with SUs, that is, it will cause SUs accessing the spectrum already occupied by a PU. Consequently, resulting in a degraded operation for both PUs and SUs. On the other hand, false-alarm error will prevent SUs from accessing non-utilized spectrum, thus degrading the performance of these users. Bearing this in mind, a common approach has been to impose low values on the missed-detection probability so as to protect the PUs a the cost of reduced SU performance. Nevertheless, despite the PUs having strict access priority to spectrum resources, it may be necessary to guarantee some Quality of Service (QoS) requirement not only for PUs but also for SUs [5]. This becomes particularly true if the license holder (i.e., the entity ruling primary operation) demands payment for secondary access to the spectrum. Accordingly, the secondary system will expect some minimum return in terms of perceived service quality by SUs.

According to the above, the main contributions of this paper are summarized in the following:

- An analytical framework based on a Discrete Time Markov Chain (DTMC) model is provided for the evaluation of sensing-based secondary spectrum access scenarios. A justification for the proposed modeling approach is also provided.
- A statistical spectrum sensing model accounting for potential sensing errors, in the form of false-alarm and missed-detection, is provided to capture the effects of such errors at a spectrum-assignment level. This model allows to use well-known expressions in the literature concerned with the false-alarm and missed-detection probabilities under several channel propagation conditions.
- The definition of the above-mentioned framework will enable to assess the potential gains that can be achieved by correctly selecting the sensing operating point which determines a particular value of the false-alarm and missed-detection probabilities.
- The suitability of the sensing operation points is determined using the Grade-of-Service (GoS) concept from "classical" telephone networks properly adapted to the primary/secondary spectrum sharing scenario. In this way, a metric is built taking into consideration the perceived service quality for both PUs and SUs.

1.2. Related work

To the best of our knowledge, our modeling approach differs from existing work [13–19], such that we use DTMCs (Discrete Time Markov Chains) as opposed to widely-used Continuous Time Markov Chains (CTMCs). The rationale behind using DTMCs instead of CTMCs is based on the fact that sensing mechanisms operate on a periodic time basis, and where the sensing periodicity is an important design parameter. Therefore, the DTMC models, which observe the state of the system at discrete time instants, can accurately model the proposed scenarios by considering the observation instants of the DTMC as the sensing instants. Moreover, DTMC models are usually easier to analyze than CTMC models and, essentially, mathematically more tractable. In addition, a statistical spectrum sensing model, which accounts for missed-detection and false-alarm errors, is proposed. This model determines the behavior of SUs in the DTMC regarding whether or not they can access a given channel at a particular time. In this sense, this also constitutes a novelty with respect to [13–18] which disregard the effects of sensing errors. Despite the fact that some considerations about sensing errors are introduced in [19], these are not related to any particular spectrum sensing mechanism (i.e., energy detection, pilot detection, etc. [12]). Conversely, we obtain the missed-detection and false-alarm values according to the well-known expressions regarding the energy detection of signals in Rayleigh fading as in [20,21], accordingly achieving higher modeling accuracy. In particular, [20] provides expressions for the false-alarm and missed-detection probabilities using energy detection in Rayleigh, Nakagami and Rician channels. Moreover, it also addresses the performance of energy detection when reception diversity schemes are employed. In addition, the work in [21] investigates how the performance of spectrum sensing using energy detection can be improved by allowing different SUs to collaborate by sharing their information. As a consequence, the proposed framework can consider several channel conditions as well as implementation alternatives by using the appropriate false-alarm and missed-detection expressions provided in the related literature.

With respect to Grade-of-Service (GoS) definition in the context of opportunistic secondary access, some efforts were provided in [18,22]. Nevertheless, the GoS metrics in [18] are strictly related to the blocking probability for both PUs and SUs disregarding other cross-effects between PUs and SUs such as the interruption probability (i.e., the

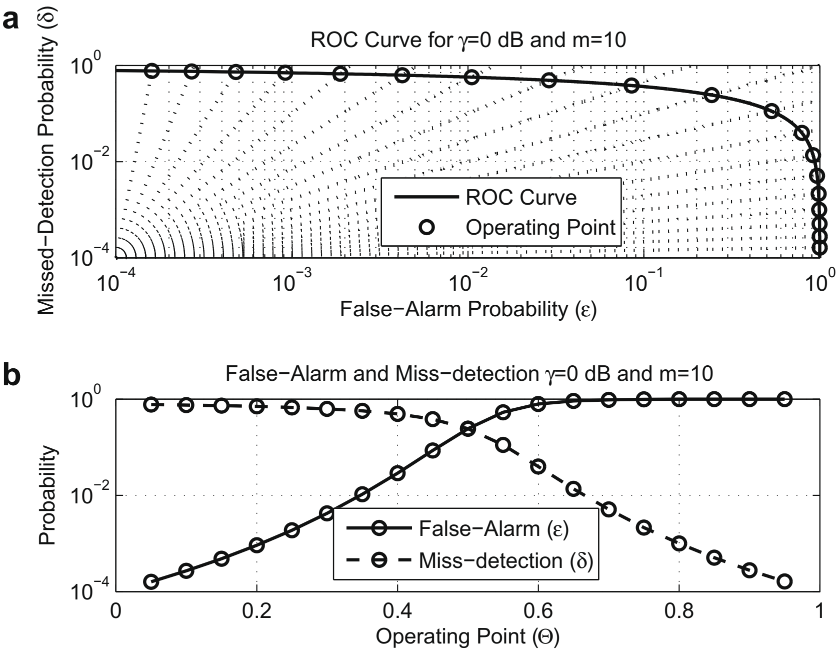

Fig. 1. (a) ROC curves in Rayleigh fading channel and (b) tradeoff between false-alarm and misdetection against the operating point.

service disruption of an SU due to PU activity) and the interference probability (i.e., the probability that both an SU and a PU share the same channel and thus cause interference). Also in [22], where a queueing framework is presented accounting for the dynamic allocation of primary and cognitive users, the GoS concept is exclusively related to the blocking probability. In this work, an improved definition for GoS is provided capturing the aforementioned effects, i.e., in addition to the blocking probability, the GoS accounts for the interference and the interruption probability of primary and secondary users, respectively.

The remainder of the paper is organized as follows. In Section 2, we present the considered spectrum sensing model and address some issues regarding the operation points of the spectrum sensing mechanisms. The DTMC model is explained and mathematically formulated in Section 3. The performance metrics of interest for numerical evaluation purposes are explained and detailed in Section 4. Section 5 deals with the performance evaluation of the proposed model. Finally, conclusions are drawn in Section 6.

2. Spectrum sensing model

We assume that spectrum sensing over a given frequency band (or channel) is performed using energy detection techniques [20]. Such method consists in measuring the energy of the received waveform over a given bandwidth W (Hz) during an observation time-window T (s). The product $m = T \cdot W$ is usually referred to as the *time-bandwidth product*. Several works, among them [20,21], have been devoted to determine closed-form analytical expressions for the false-alarm and misdetection (or, conversely, detection) probabilities under various channel conditions. Basically, the energy detection scheme performs a binary hypothesis on the occupancy of a band or channel: $\mathcal{H}_0$ if the channel is free and $\mathcal{H}_1$ if the channel is occupied. Then, the false-alarm and misdetection, ε and δ accordingly, can be defined as:

$$\varepsilon = \Pr[Y > \lambda | \mathcal{H}_0 \text{ is true}] \triangleq G_\varepsilon(\lambda), \tag{1}$$

$$\delta = \Pr[Y < \lambda | \mathcal{H}_1 \text{ is true}] \triangleq G_\delta(\lambda), \tag{2}$$

where the decision statistic Y is compared to the decision threshold λ in order to determine the occupancy status of the channel. Accordingly, expressions for $G_\varepsilon(\lambda)$ and $G_\delta(\lambda)$ can be determined by accounting several channel conditions and cooperation schemes [20,21]. For example, in the case of spectrum sensing in Rayleigh fading environments we have [21]:

$$G_\varepsilon(\lambda) = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{3}$$

$$\begin{aligned} G_\delta(\lambda) = {} & e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\gamma}{\gamma}\right)^{m-1} \\ & \times \left(e^{-\frac{\lambda}{2(1+\gamma)}} - e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\lambda\gamma}{2(1+\gamma)}\right)^k \right), \end{aligned} \tag{4}$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are the complete and incomplete gamma functions, respectively, and γ is the average signal-to-noise ratio.

Of particular interest is to determine the relationship between ε and δ through the so-called *Receiver Operating Characteristic* (ROC) curves where ε is plotted against δ for some given average signal-to-noise ratio γ and time-bandwidth product m. Formally, from (1) we can express $\lambda = G_\varepsilon^{-1}(\varepsilon)$ and by using (2) we obtain $\delta = G_\delta(G_\varepsilon^{-1}(\varepsilon))$ which results in the ROC curve in Fig. 1a for the particular case of sensing in Rayleigh fading. More specifically, we isolate λ from expression (3) and substitute it in expression (4).

Each point of such curve, hereon indicated by the pair $(\delta_0, \varepsilon_0)$, denotes a possible operating point (OP) for the sensing mechanism. In Fig. 1a a possible set of feasible OPs is marked by circles. Note that the existing tradeoff between false-alarm and misdetection probability where the low values of ε are attained at high values of δ and vice versa.

By appropriately selecting a specific decision threshold value $\lambda = \lambda_0$ we obtain a particular value for the OP $(\delta_0, \varepsilon_0)$. It is worth mentioning that the function mapping between λ_0 and $(\delta_0, \varepsilon_0)$ is bijective, i.e., there is a one-to-one correspondence between λ_0 and $(\delta_0, \varepsilon_0)$ values in both directions.

For the sake of representation, rather than using the decision threshold λ (which depends on the decision statistic Y and, consequently, on the measured signal energy) we define the operating-point mix Θ, with $0 \leqslant \Theta \leqslant 1$, as:

$$\Theta \triangleq \frac{\log(\varepsilon/\varepsilon_{\min})}{\log(\delta/\delta_{\min}) + \log(\varepsilon/\varepsilon_{\min})}, \tag{5}$$

where $\varepsilon_{\min}$ and $\delta_{\min}$ are the minimum operating values for the false-alarm and misdetection probabilities respectively given by the ROC curve (see that $\varepsilon_{\min} = \delta_{\min} = 10^{-4}$ in Fig. 1a). The values of $\varepsilon_{\min}$ and $\delta_{\min}$ can be regarded as the resolution of the sensing mechanism and consequently they are determined by the sensing equipment characteristics. Then, after some algebra manipulation, it follows that:

$$\delta = \delta_{\min}\left(\frac{\varepsilon}{\varepsilon_{\min}}\right)^{\left(\frac{1}{\Theta}-1\right)}, \tag{6}$$

which is plotted in Fig. 1a, for different values of $0 \leqslant \Theta \leqslant 1$, which results in the set of dashed lines crossing the origin of coordinates at $(\delta_{\min}, \varepsilon_{\min})$. For each particular value of $\Theta = \Theta_0$ we obtain a particular OP $(\delta_0, \varepsilon_0)$ which is represented by the circles in Fig. 1a denoting the intersection of the line equation given by (6) with the ROC curve.

In this way, we have a normalized parameterization through parameter Θ for the feasible OPs of the sensing mechanism. Note that, see Fig. 1b, for $0 < \Theta < 0.5$ we have that $\delta > \varepsilon$; for $\Theta = 0.5$ we obtain $\delta = \varepsilon$; and finally, for $0.5 < \Theta < 1$ we have $\delta < \varepsilon$. Then, the value of Θ will be used to represent the full range of possible cases and determine the most suitable OP for different traffic conditions.

In addition, for a longer time T devoted to sensing purposes, lower false-alarm and missed-detection probabilities can be attained. Indeed, this can be seen in Fig. 2, which plots the ROC curve for several values of the time-bandwidth product (m). For a particular target missed-detection probability value ($\delta = 10^{-1}$) several corresponding false-alarm values are obtained as indicated by the OPs in Fig. 2.

3. DTMC model formulation

The proposed DTMC model accounts for the spectrum occupancy of PUs and SUs in a shared spectrum scenario. For simplicity reasons, it is supposed that the whole spectrum bandwidth is partitioned into a total number of C channels (bands) to be shared among both PUs and SUs. It is further assumed that both PUs and SUs demand a single channel for transmission purposes. These assumptions, although simplifying, will keep the algebra at an understandable and tractable level while still capturing the essence of the considered problem. If desirable, more elaborate shared bandwidth models can be easily considered and adapted to the model presented here. It is

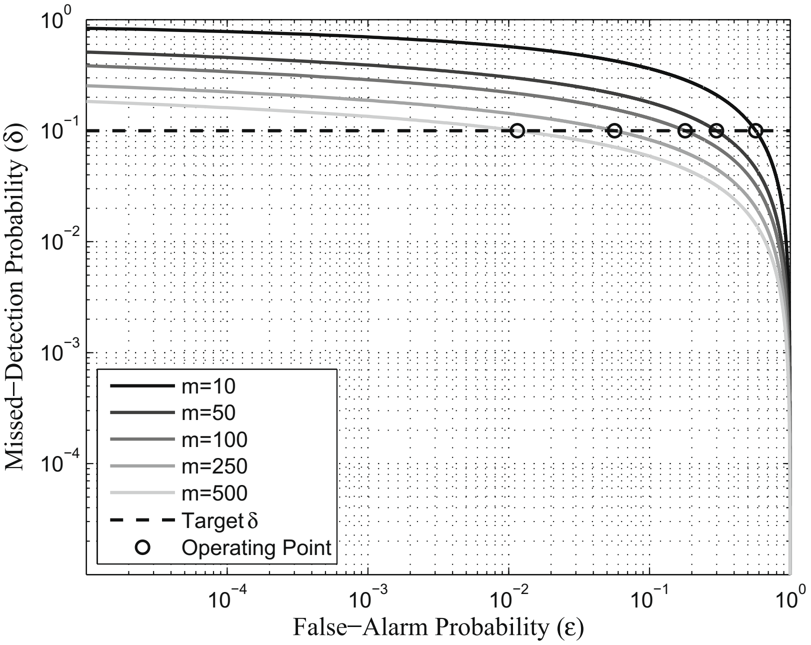

Fig. 2. ROC curve varying the time-bandwidth product (m) for SNR of $\gamma = 0$ dB.

also assumed that the SN implements SpHO (i.e. Spectrum HandOver) mechanisms, so that an SU is able to release a channel which is suddenly occupied by a PU and move to another channel, provided there is a free one, or to interrupt its session otherwise.

In a DTMC we observe the system state at discrete time instants $\{t_0, t_1, t_2, \ldots, t_n, \ldots\}$, with $t_n = t_0 + n \cdot \Delta T$ and periodicity ΔT, where ΔT also specifies at which time instants primary spectrum information is made available. In addition, let $I_n = (t_n, t_{n+1}]$ define the nth time interval between two successive observation times. The DTMC model formulation involves a number of steps which are presented in the following subsections.

3.1. State space definition

Let $N_p(t_n)$ and $N_s(t_n)$ be independent stochastic processes indicating the number of PUs and SUs in the system at time t_n. Then, let $\mathbf{X}_n = S_{(i,j)} = \{N_p(t_n) = i, N_s(t_n) = j\}$ represent a state of the DTMC at time t_n. Then, if C channels are available, the considered state space $\mathscr{S}$ must contain all possible states $S_{(i,j)}$ which fulfill both $i \leqslant C$ and $j \leqslant C$, formally:

$$\mathscr{S} = \left\{S_{(i,j)} : i \leqslant C, j \leqslant C\right\}. \tag{7}$$

However, for a correct spectrum use (i.e., with no spectrum collisions due to a PU and SU sharing the same channel), the number of PUs (i) plus the number of SUs (j) must not exceed the total number of available channels (C). In addition, in the presence of spectrum detection errors, an SU might be erroneously assigned to a band already in use by a PU. Then, for convenience, we define two subsets of $\mathscr{S}$ accounting for those states that imply spectrum collision, i.e.

$$\mathscr{S}_c = \left\{S_{(i,j)} : i + j > C\right\}, \tag{8}$$

and those states which are collision-free, i.e.

$$\mathscr{S}_{nc} = \left\{S_{(i,j)} : i + j \leqslant C\right\}. \tag{9}$$

3.2. Detection of primary spectrum occupancy

At a given time t_n, let the state of the DTMC be $\mathbf{X}_n = S_{(i,j)} \in \mathscr{S}$. At this same time instant, the spectrum occupancy information is made available to the SN side (either to some centralized infrastructure-based entity or to a specific SU). Due to spectrum detection errors, the observed state at time t_n using such erroneous information may be $\mathbf{Y}_n = S_{(k,j)} \in \mathscr{S}$, i.e. $\mathbf{Y}_n \neq \mathbf{X}_n$, with k denoting the number of detected PUs (note the number of SUs at time t_n, j, is known by the SN, so it is not subject to errors). Consequently, the aim is to determine the conditioned probability of detecting k PUs when there are in fact i PUs in the system at time t_n, i.e.

$$b_{(k,i)} = \Pr[\mathbf{Y}_n = S_{(k,j)} | \mathbf{X}_n = S_{(i,j)}]. \tag{10}$$

It can be shown, here omitted for space reasons, that the probability $b_{(k,i)}$ in (10) can be analytically derived considering false-alarm and misdetection probabilities, i.e. δ and ε, as

$$b_{(k,i)} = \sum_{m=\max(0,i-k)}^{\min(i,C-k)} \binom{C-i}{m+k-i} \cdot \varepsilon^{m+k-i} \cdot \bar{\varepsilon}^{C-m-k} \cdot \binom{i}{m} \cdot \delta^m \cdot \bar{\delta}^{i-m} \tag{11}$$

with $\bar{\varepsilon} \triangleq 1 - \varepsilon$ and $\bar{\delta} \triangleq 1 - \delta$.

Then, $b_{(k,i)}$ provides the mapping function, between the so-called *true state space* given by states $\mathbf{X}_n = S_{(i,j)} \in \mathscr{S}$ and the *detected state space* given by states $\mathbf{Y}_n = S_{(k,j)} \in \mathscr{S}$. Since the SN operation will be based on the knowledge of $\mathbf{Y}_n$ instead of $\mathbf{X}_n$, the values of δ and ε will considerably affect the performance of such system and lead, in the worst case, to an ineffective operation.

3.3. Arrival and departure processes

Let $N^A \in \left\{N^{PA}, N^{SA}\right\}$ along with $N^D \in \left\{N^{PD}, N^{SD}\right\}$ denote the number of arrivals and departures of PUs and SUs respectively in I_n(i.e. in a time interval of duration ΔT). In addition, both N^A and N^D are independent from the time instant t_n and independent from each other.

Given PUs and SUs arrive at the system according to a Poisson distribution with rates λ_p and λ_s respectively, the probability that k arrivals occur in I_n, P_k^A, is given by [23]:

$$P_k^A = \Pr[N^A = k] = \left[(\lambda\Delta T)^k / k!\right] e^{-\lambda\Delta T}, \tag{12}$$

where for $\lambda \in \{\lambda_p, \lambda_s\}$ we will refer to $P_k^A \in \{P_k^{PA}, P_k^{SA}\}$.

If the session duration is exponentially distributed with mean $1/\mu$ (i.e., rate μ), the probability of a session departure in I_n is [23]:

$$P^D = 1 - e^{-\mu\Delta T}. \tag{13}$$

Then, the probability of having k-out-of-m departures in I_n, P_k^D, is given by the binomial distribution [23]:

$$P_k^D = \Pr[N^D = k] = \binom{m}{k} \left(1 - e^{-\mu\Delta T}\right)^k \left(e^{-\mu\Delta T}\right)^{m-k}, \tag{14}$$

where for $\mu \in \{\mu_p, \mu_s\}$ we will refer to $P_k^D \in \{P_k^{PD}, P_k^{SD}\}$.

For the sake of algebra tractability, we assume in the remainder of the paper that a session arriving in I_n will not depart in the same I_n. Note that this implies that both ΔT and the duration of a session must be carefully chosen such that $\Delta T \ll 1/\mu$ with $\mu \in \{\mu_p, \mu_s\}$ and where $1/\mu$ is the average session duration. In addition, we disregard the order in which the session arrivals and departures occur in a given I_n by considering the resulting net number of users, i.e., those obtained after subtracting the departures and adding the new arrivals. Note that enabling multiple arrivals in one ΔT will affect the decision process on whether an SU can be assigned or not given that the detection information is retrieved only at times t_n. This also constitutes a differentiating aspect with respect to other approaches to the same problem such as in [13–15,19,16,17].

3.4. Channel assignment and de-assignment processes

The number of PU/SU spectrum assignments and de-assignments in I_n, $N_a \in \left\{N_a^P, N_a^S\right\}$ and $N_d \in \left\{N_d^P, N_d^S\right\}$, will depend on the spectrum occupancy given by the true or detected states at time t_n, i.e. $\mathbf{X}_n$ or $\mathbf{Y}_n$, and on the number of N^A arrivals and N^D departures in time interval I_n. This number of arrivals and departures will eventually lead to a number of channel assignments and de-assignments depending on the true or detected spectrum occupancy at time t_n.

Subsequently, probability expressions for spectrum assignments and de-assignments in I_n for PUs/SUs are derived.

3.4.1. Primary users

Let the true state be $\mathbf{X}_n = S_{(i,j)}$; the probability of assigning $N_a^P = k$ PUs in I_n provided there are $N_d^P = l \leqslant i$ PU de-assignments in I_n, $a^P_{(i,j,k,l)}$, is the conditioned probability:

$$a^P_{(i,j,k,l)} = \Pr[N_a^P = k|\mathbf{X}_n = S_{(i,j)}, N_d^P = l] = \begin{cases} \Pr[N^{PA} = k] = P_k^{PA}, \\ \text{if } i - l + k < C, \\ \Pr[N^{PA} \geqslant k] = 1 - \sum\limits_{m=0}^{k-1} P_m^{PA}, \\ \text{if } i - l + k = C \end{cases} \tag{15}$$

with P_k^{PA} given in (12). In words, we may express (15) saying that the probability of assigning exactly k PUs is the probability of having exactly k PU arrivals if more than k channels are available, and the probability of having at least k PU arrivals if exactly k channels are available. Clearly, the probability of assigning more PUs than the available channels is zero. Implicitly in (15) we consider that k PU assignments are made upon l PU de-assignments, thus using the assumption of disregarding the order in which arrivals and departures occur in I_n which was previously mentioned in Section 3.3.

Again, let the true state be $\mathbf{X}_n = S_{(i,j)}$; the probability of de-assigning $N_d^P = k$ PUs in I_n, where $0 \leqslant k \leqslant i$ (i.e. we can only de-assign those already assigned prior to t_n), depends on the number of PU departures in I_n:

$$d^P_{(i,j,k)} = \Pr[N_d^P = k|\mathbf{X}_n = S_{(i,j)}] = \Pr[N^{PD} = k] = P_k^{PD} \tag{16}$$

with P_k^{PD} given in (14). Note that we have made use of the assumption that a new arrival in I_n will not depart in I_n by specifying that the number of de-assignments is bounded as $0 \leqslant k \leqslant i$ in I_n. For any other value of k, the probability in (16) is zero.

Note that the operation of PUs (i.e., the prioritized users) is autonomous of the activity of SUs, i.e., the channel assignment and de-assignment probabilities given in (15) and (16) strictly depend on the number of primary arrivals and departures through probabilities P_k^{PA} and P_k^{PD} correspondingly.

3.4.2. Secondary users

The channel assignment and de-assignment processes from the SN perspective will be based on the detected primary spectrum occupancy which is subject to detection errors (i.e., δ and ε). Such spectrum occupancy information is provided through the probability $b_{(k,i)}$ in (11).

Let the true state be $\mathbf{X}_n = S_{(i,j)}$; the probability of assigning $N_a^S = k > 0$ SUs in I_n given we have $N_d^S = l \leqslant j$ SU de-assignments in I_n, $a^S_{(i,j,k,l)}$, will depend on the detected state at t_n, $\mathbf{Y}_n = S_{(m,j)}$ and on the number of SU arrivals as:

$$\begin{aligned} a^S_{(i,j,k,l)} &= \Pr[N_a^S = k|\mathbf{X}_n = S_{(i,j)}, N_d^S = l] = \sum_{m=0}^{C-k-j+l} \Pr[N_a^S \\ &= k|\mathbf{Y}_n = S_{(m,j)}, N_d^S = l] \cdot b_{(m,i)} \\ &= \sum_{m=0}^{C-k-j+l} \bar{a}^S_{(m,j,k,l)} \cdot b_{(m,i)}, \end{aligned} \tag{17}$$

where the total probability formula has been used to relate the true state $\mathbf{X}_n = S_{(i,j)}$ with the detected state $\mathbf{Y}_n = S_{(m,j)}$ through probabilities $b_{(k,i)}$. In particular, (17) states that $N_a^S = k$ SUs will be assigned provided the detected number of PUs, m, fulfills $m + j + k - l \leqslant C$, i.e., there are at least k detected free channels for secondary use provided that we also have l SU de-assignments. In addition, the number of k SU assignments in state $\mathbf{X}_n = S_{(i,j)}$ is bounded by $0 < k \leqslant C - i - j + l$, omitting the case $k = 0$ which will be treated separately. Finally, $\bar{a}^S_{(m,j,k,l)}$ in (17) is obtained similar to (15) as:

$$\bar{a}^S_{(m,j,k,l)} = \begin{cases} P_k^{SA}, & \text{if } m + j - l + k < C, \\ 1 - \sum\limits_{r=0}^{k-1} P_r^{SA}, & \text{if } m + j - l + k = C. \end{cases} \tag{18}$$

For the specific case of no SU assignments (i.e. $k = 0$), the probability of assigning $k = 0$ SUs is the probability of assigning $k = 0$ SUs when there is at least one free detected channel or the probability that there are no detected free channels, i.e.:

$$\begin{aligned} a^S_{(i,j,0,l)} &= \Pr[N_a^S = 0|\mathbf{X}_n = S_{(i,j)}, N_d^S = l] \\ &= \sum_{m=0}^{C-j+l} \bar{a}^S_{(m,j,0,l)} \cdot b_{(m,i)} + \sum_{m=C-j+l}^{C} b_{(m,i)}. \end{aligned} \tag{19}$$

As for the de-assignment processes of SUs, there are mainly three independent events which imply an SU de-assignment: in the first place, a number of $N_d^{S,S}$ SUs may be de-assigned provided detection at time t_n determines that there are $N_d^{S,S}$ SUs sharing the same channel with PUs. Secondly, a number of $N_d^{S,SC}$ SUs may be de-assigned in I_n simply because their sessions have ended (here, SC stands for service completion).

Then, let the true state be $\mathbf{X}_n = S_{(i,j)}$; the probability of de-assigning $N_d^{S,S} = k$ SUs in I_n due to detection of state $\mathbf{Y}_n = S_{(m,j)}$ at time t_n, given the number of de-assignments due to service completion is $N_d^{S,SC} = l$, is given by:

$$\begin{aligned} \Pr[N_d^{S,S} = k|\mathbf{X}_n = S_{(i,j)}, N_d^{S,SC} = l] &= \Pr[m + j - l \\ &= C + k] = b_{(C+k-j+l,i)}, \end{aligned} \tag{20}$$

provided that $0 < k \leqslant j - l$. Accordingly, the probability of no SU de-assignments due to detection of state $\mathbf{Y}_n = S_{(m,j)}$ is:

$$\Pr[N_d^{S,S} = 0|\mathbf{X}_n = S_{(i,j)}, N_d^{S,SC} = l] = 1 - \sum_{k=1}^{j-l} b_{(C+k-j+l,i)}. \tag{21}$$

Then, from (20) and (21), we can write:

$$d^{S,S}_{(i,j,k,l)} = \Pr[N_d^{S,S} = k|\mathbf{X}_n = S_{(i,j)}, N_d^{S,SC} = l] = \begin{cases} b_{(C+k-j+l,i)} \\ \text{if } 0 < k \leqslant j - l, \\ 1 - \sum\limits_{r=1}^{j-l} b_{(C+r-j+l,i)} \\ \text{if } k = 0. \end{cases} \tag{22}$$

On the other hand, the probability of de-assigning k SUs in I_n due service completions is given by (similar to (16)):

$$d^{S,SC}_{(i,j,k)} = \Pr[N^{S,SC}_d = k|\mathbf{X}_n = S_{(i,j)}] = \Pr[N^{SD} = k] = P^{SD}_k. \qquad (23)$$

We can express the global probability of de-assigning k SUs in I_n (i.e. without specifying if the de-assignment is due to detection or due to session completion) as:

$$d^{S}_{(i,j,k)} = \Pr[N^{S}_d = k|\mathbf{X}_n = S_{(i,j)}] = \sum_{r=0}^{k} d^{S,S}_{(i,j,k-r,r)} \cdot d^{S,SC}_{(i,j,r)}. \qquad (24)$$

3.5. Transition probabilities

The transition probabilities between each pair of states $S_{(k,l)} \to S_{(i,j)}$ in our DTMC model can be expressed as [23]:

$$\begin{aligned} P_{(i,j|k,l)} &= \Pr[X_{n+1} = S_{(i,j)}|X_n = S_{(k,l)}] = \Pr[N_p(t_{n+1}) \\ &= i, N_s(t_{n+1}) = j|N_p(t_n) = k, N_s(t_n) = l] \\ &= \Pr[N_p(t_{n+1}) = i|N_p(t_n) = k, N_s(t_n) \\ &= l] \cdot \Pr[N_s(t_{n+1}) = j|N_p(t_n) = k, N_s(t_n) = l], \end{aligned} \qquad (25)$$

where the conditional independence of processes $N_p(t_n)$ and $N_s(t_n)$ has been used. Probabilities $P_{(i,j|k,l)}$ are the entries of the transition probability matrix $\mathbf{P}$, from which the steady state probabilities, $P_{(i,j)}$, of the DTMC will be determined [23].

Then, after some algebraic manipulation, the general transition probability $S_{(i,j)} \to S_{(i+N,j+M)}$ with $-i \leqslant N \leqslant C-i$ and $-j \leqslant M \leqslant C-j$, can be expressed as:

$$\begin{aligned} P_{(i+N,j+M|i,j)} = &\left(\sum_{k=\max(-N,0)}^{i} a^{P}_{(i,j,N+k,k)} \cdot d^{P}_{(i,j,k)}\right) \\ &\cdot \left(\sum_{k=\max(-M,0)}^{j} a^{S}_{(i,j,M+k,k)} \cdot d^{S}_{(i,j,k)}\right) \end{aligned} \qquad (26)$$

with parameters in (26) previously defined in Section 3.4.

From the resulting transition probability matrix $\mathbf{P}$ defined through (26), we obtain the true steady state probabilities, $P_{(i,j)}$, for each true state $S_{(i,j)}$ in the state space $\mathscr{S}$.

On the other hand, it is also relevant to determine the steady state probabilities of the detected states (i.e. including possible sensing errors), which are computed as:

$$P'_{(i,j)} = \sum_{n=0}^{C} b_{(i,n)} \cdot P_{(n,j)}. \qquad (27)$$

Then, by considering $P\prime_{(i,j)}$ instead of $P_{(i,j)}$ we obtain the metrics computed from the SN side, which account for possible sensing errors.

4. Performance metrics

The classical Grade-of-Service (GoS) concept in classical telephone networks [24] is adopted to the opportunistic spectrum access scenarios. The GoS metrics, introduced hereafter, will be computed from performance metrics derived from the steady state probabilities $P_{(i,j)}$ and $P'_{(i,j)}$ obtained as specified in the previous section. In particular, the performance metrics of interest for the GoS computation are: primary and secondary users blocking probabilities, interruption probability and interference probability.

4.1. Blocking probability

Blocking occurs whenever a new user cannot be assigned a channel given all channels are occupied, in the case of a PU, or thought to be occupied, in the case of an SU. Accordingly, the blocking probability for PUs, P^P_B, can be computed from the true steady state probabilities, $P_{(i,j)}$, as:

$$P^P_B = \sum_{j=0}^{C} P_{(C,j)}. \qquad (28)$$

On the other hand, the SU blocking probability, P^S_B, is given by:

$$P^S_B = \sum_{i=0}^{C} \sum_{j=C-i}^{C} P'_{(i,j)}. \qquad (29)$$

Notice that $P'_{(i,j)}$ is used instead of $P_{(i,j)}$ to indicate that secondary blocking may occur due to the sensing of all channels as occupied while this may in fact not be true.

4.2. Interruption probability

Interruption of secondary service occurs whenever an SU is forced to release a channel, before its session has ended, due to primary activity. To compute the interruption probability, P_D, the average number of secondary users, N_s, can be considered:

$$N_s = \sum_{S_{(i,j)} \in \mathscr{S}} j \cdot P_{(i,j)} \qquad (30)$$

can be interpreted as the average served SU traffic, i.e. $T^{\text{served}}_S = N_s$ [23]. Furthermore, it can be expressed as:

$$T^{\text{served}}_S = T_S \cdot \left(1 - P^S_B\right) \cdot (1 - P_D), \qquad (31)$$

meaning that the served traffic (T^{served}_S) is the offered traffic ($T_S = \lambda_S/\mu_S$) which is not blocked nor interrupted. By rearranging (31) we obtain:

$$P_D = 1 - \frac{T^{\text{served}}_S}{T_S\left(1 - P^S_B\right)} = 1 - \frac{N_S}{\frac{\lambda_S}{\mu_S}\left(1 - P^S_B\right)} b \qquad (32)$$

with P^S_B defined in (29) and N_S given in (30).

4.3. Interference probability

The interference probability, P_I, is defined as the probability of being in state $S_{(i,j)} \in \mathscr{S}_c$ with the set $\mathscr{S}_c$ defined in (8), i.e., the probability that at least a channel is simultaneously occupied by both a PU and an SU, then:

$$P_I = \sum_{S_{(i,j)} \in \mathscr{S}_c} P_{(i,j)}. \qquad (33)$$

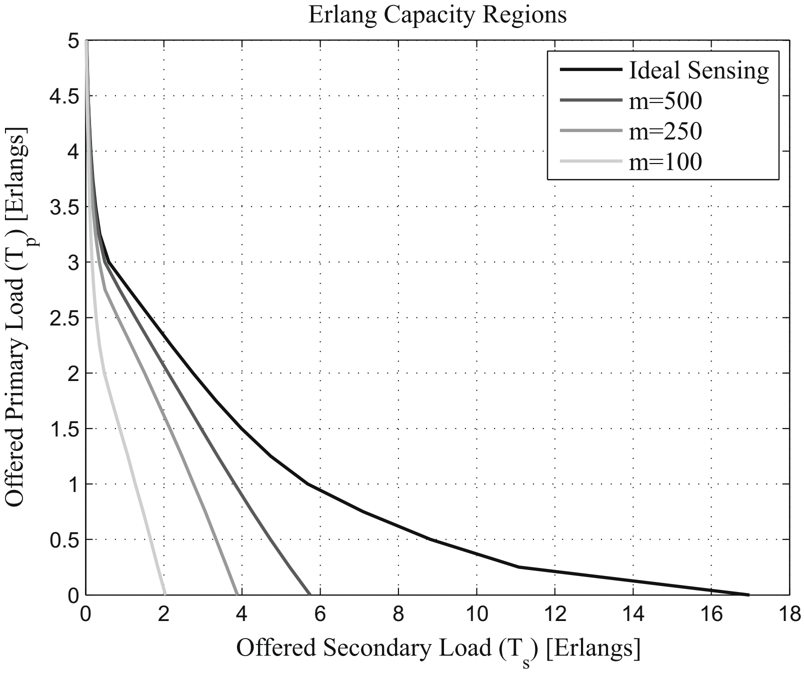

Fig. 3. Erlang Capacity regions varying the time-bandwidth product (m) for target $\mathrm{GoS}^{A*} = 5 \cdot 10^{-3}$.

4.4. Grade-of-Service definitions

Primary GoS (GoS^P) is derived from the blocking probability given in (28) and the interference probability in (33) as follows[2]:

$$\mathrm{GoS}^P = \left(P_B^P + \omega_P \cdot P_I\right)/(1+\omega_P), \tag{34}$$

where $\omega_P > 1$ is a weight factor indicating a higher penalty of interference with respect to blocking from the PUs' perspective.

We consider the SU blocking probability P_B^S, as in (29), along with the interruption probability P_D, as in (32), to define the secondary GoS (GoS^S) as follows:

$$\mathrm{GoS}^S = \left(P_B^S + \omega_S \cdot P_D^S\right)/(1+\omega_S) \tag{35}$$

with $\omega_S > 1$ the corresponding secondary weight factor indicating that interruption is more harmful than blocking.

Finally, we may define the aggregate GoS (GoS^A) as:

$$\mathrm{GoS}^A = \left(\mathrm{GoS}^S + \omega_A \cdot \mathrm{GoS}^P\right)/(1+\omega_A), \tag{36}$$

which jointly accounts for the individual GoS of both PUs and SUs and where we consider that the weight factor $\omega_A > 1$ will prioritize PU quality since they have strict precedence as primary (licensed) users of the shared spectrum. Note that ω_P, ω_S and ω_A should be chosen adequately in accordance to the expected perceived GoS of each user type (i.e., PU or SU). Nevertheless, note that these values are empirical and depend on the subjective perception of the Grade-of-Service metric.

5. Performance evaluation

In this section, we evaluate the proposed model by considering the performance metrics presented in Section 4. We consider a spectrum partition with $C = 8$ channels. The spectrum sensing periodicity, unless otherwise stated, is $\Delta T = 2$ seconds. For the spectrum sensing model, the cases considered in Figs. 1 and 2 are employed, i.e., the Rayleigh channel with signal-to-noise ratio of $\gamma = 0$ dB. The weight factors for GoS computation in (34)–(36) are given by $\omega_S = 10$, $\omega_P = 20$ and $\omega_A = 10$.

5.1. Erlang Capacity

The Erlang Capacity of a system with limited resources refers to the maximum amount of offered traffic it may handle provided some quality of service requirements are met [25]. In the case of primary/secondary spectrum sharing, the interest is on the maximum primary and secondary traffic that can be offered such that some aggregate GoS requirement (i.e., accounting for both PUs and SUs) is satisfied. Mathematically, this can be expressed as:

$$\mathbb{E} = \left\{(T_S, T_P) : \mathrm{QoS}^A \leqslant \mathrm{QoS}^{A*}\right\}, \tag{37}$$

with QoS^A defined in (36) and where QoS^{A*} indicates a target value for the aggregate GoS.

According to the above definition, the Erlang Capacity may be regarded as a region comprising the pairs of (T_S, T_P) offered traffic values which yield satisfactory GoS

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[2] For convenience, a normalized version of the $\mathrm{GoS} \in [0, 1]$ is used, where $\mathrm{GoS} \to 1$ means degraded operation while $\mathrm{GoS} \to 0$ means improved operation.

requirements. Accordingly, Fig. 3 shows the Erlang Capacity regions (defined as the areas below the Erlang Capacity limits plotted in the figure) considering several time-bandwidth product (m) values. For the sake of comparison, the case where ideal sensing, and thus full awareness of PU activity, is also considered. As expected, the ideal sensing case translates into a larger Erlang Capacity region provided a better use of unoccupied spectrum resources can be achieved by SUs given their fully-aware information about PU spectrum usage. For the case of non-ideal sensing, the higher the time-bandwidth product (m) the better spectrum resources are being utilized. This is due to the

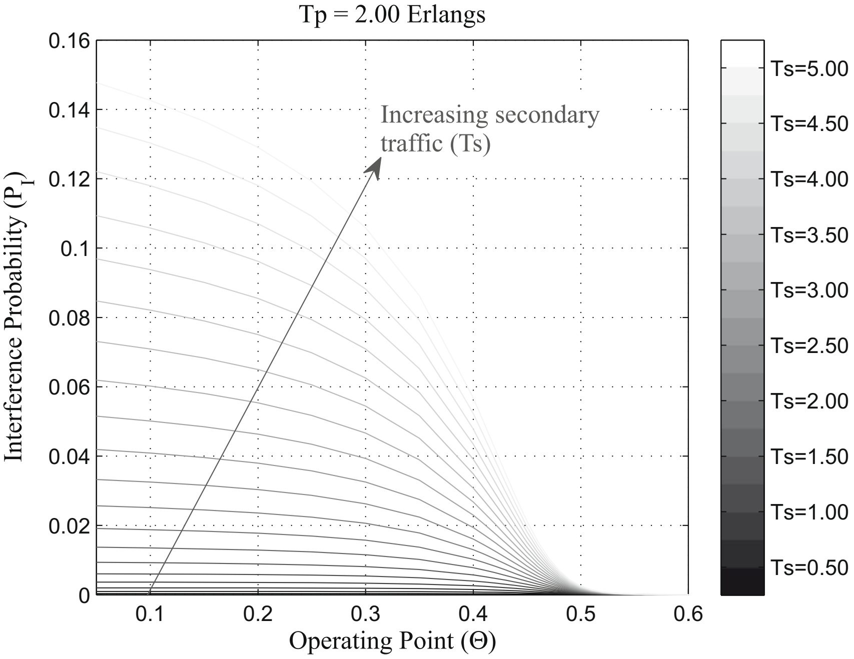

Fig. 4. Interference probability against the OP for several traffic conditions.

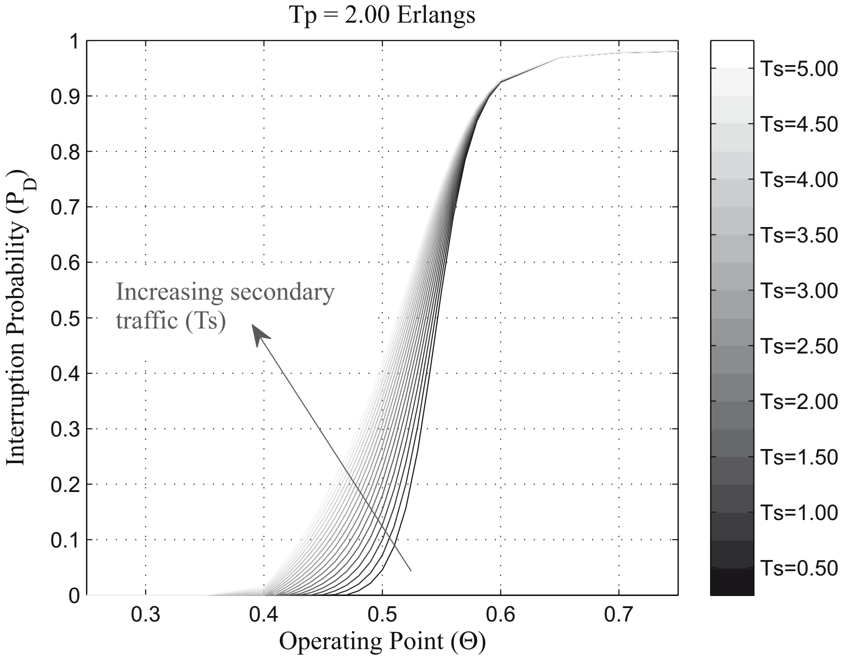

Fig. 5. Interruption probability against the OP for several traffic conditions.

fact that higher m values imply lower false-alarm probabilities (given the missed-detection probability is fixed) as can be observed from Fig. 2. In addition, it can be observed that for increased primary offered traffic values (e.g. $T_P > 2.5$ Erlangs), the Erlang Capacity region narrows towards lower values of offered secondary traffic (T_S), indicating that if a high number of PUs are occupying the spectrum (which have strict priority) then hardly no SUs are able to access the spectrum.

It is worth mentioning that the increase of the time-bandwidth product to reduce the false-alarm probability comes at the cost of increased sensing times which in turn degrade the achievable throughput as identified in [26,27]. Therefore, although Fig. 3 indicates that the higher the value of m the better, the effect on throughput should be also taken into consideration.

5.2. Quality-of-service provisioning in sensing-based spectrum sharing scenarios

Concerning the experienced QoS for both PUs and SUs, GoS metrics, defined in Section 4.4, indicate that the interference and interruption probabilities are the major causes for PU and SU dissatisfactions, respectively. Then, we are interested in finding the most suitable OP of the sensing mechanism so that some satisfaction balance between PUs and SUs can be achieved. Accordingly, Figs. 4 and 5 show the interference and interruption probabilities against the sensing OP (Θ) under varying SU traffic and an offered PU traffic of $T_P = 2$ Erlangs. As for the interference probability in Fig. 4, the OP values of $\Theta \to 0$ indicate higher missed-detection probabilities (δ) as opposed to lower false-alarm probabilities (ε). Consequently, we note an increased interference due to an excess of SUs accessing the spectrum and erroneously detecting occupied channels as free. Conversely, when the value of Θ is increased towards 1, missed-detection decreases, thus, causing lower interference. The opposite behavior can be seen in Fig. 5 where the interruption probability is plotted. In this case, the low false-alarm (i.e., $\Theta \to 0$) benefits SUs since higher spectrum access chances are experienced. On the other hand, if false-alarm is increased (meaning $\Theta \to 1$), the detection of free channels as occupied will force SUs to defer their communication, thus, causing the interruption probability to rise. For both the interference and interruption probabilities, the higher the secondary offered traffic (T_S), the higher degradation is observed.

In Fig. 6, the aggregate GoS (GoS^A) as defined in (36) is plotted for different offered traffic configurations (see Fig. 6a–c). By observing Fig. 6, we realize that by appropriately choosing the sensing OP (Θ) a minimum value of aggregate GoS can be achieved, thus improving the perceived satisfaction of both PUs and SUs. In addition, note that as the offered primary traffic increases as $T_P = 1, 2, 3$ Erlangs in Fig. 6a–c, respectively, the suitable OP value moves towards increased values of Θ in order to protect the increasing number of PUs in the system. This is in line with what depicted in Fig. 4 where values of $\Theta \to 1$ are required in order to lessen the interference probability experienced by PUs.

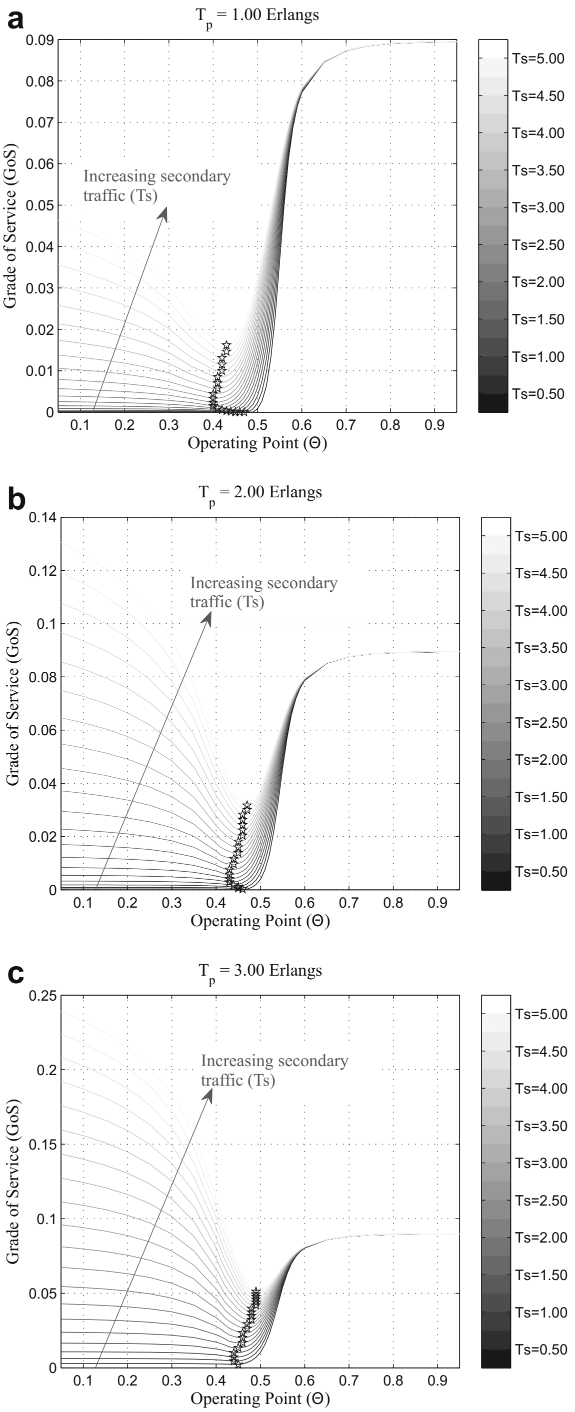

Fig. 6. Grade-of-Service (GoS) as a function of the operating point for different PU and SU traffic load conditions.

In addition to Fig. 6, the suitable OP values (i.e. those that minimize the perceived aggregate GoS) are provided in Table 1 for specific primary and secondary offered traffic. These values correspond to some of the star-shaped marks in Fig. 6a–c. It is worthwhile noting that, for low offered primary and secondary traffic, a range of OP values,

Table 1
Suitable operating points for several offered primary and secondary traffic values, T_s and T_p (expressed in Erlangs).

Suitable OP (Θ^*)			
T_S	$T_P = 1.00$	$T_P = 2.00$	$T_P = 3.00$
0.50	[0,0.45]	[0,0.45]	0.44
1.00	[0,0.45]	[0,0.44]	0.44
1.50	[0,0.43]	0.43	0.46
2.00	[0,0.41]	0.43	0.46
2.50	0.40	0.44	0.47
3.00	0.40	0.45	0.48
3.50	0.41	0.46	0.48
4.00	0.42	0.46	0.49
4.50	0.42	0.46	0.49
5.00	0.43	0.47	0.49

denoted as $[\cdot,\cdot]$ in Table 1, provides the minimum GoS^A. In these cases, interference with PUs is kept low and, thus, values of $\Theta \rightarrow 0$, which benefit SUs, can be selected. However, as secondary and primary traffic increases, so does the probability of interference (see Fig. 4), therefore increased values of Θ are needed in order to protect the PUs. Then, the higher the primary traffic, the less flexible is the selection of the suitable OP, which is, on the other hand, somewhat expected.

Finally, in Fig. 7, the effect of the sensing periodicity value (ΔT) on the perceived GoS is plotted. As the sensing periodicity increases, so does the interference probability given that secondary access is based on an older, and potentially out-of-date, spectrum occupancy information. Then, as ΔT increases, the suitable sensing OP is shifted towards values of $\Theta \rightarrow 1$ given this protects PUs by decreasing the missed-detection probability.

6. Conclusion

In this paper, a framework for the evaluation of sensing-based secondary spectrum access has been motivated and further presented. The main purpose of the framework is to determine the suitable sensing operating point so that requirements in terms of Grade-of-Service could be satisfied for both primary and secondary users. In this sense, the operating point of a sensing mechanism using threshold-based energy detection has been parameterized, given by Θ, in order to capture the existing tradeoff between missed-detection and false-alarm probabilities which negatively affect spectrum awareness. A complete and detailed DTMC model has been formulated describing the spectrum access of both primary and secondary users. This model includes the effect of erroneous sensing so that missed-detection and false-alarm is accounted and its impact on primary and secondary users assessed. In this sense, missed-detection causes the interference between PUs and SUs to rise, thus degrading the PUs which require non-harmful operation. On the contrary, false-alarm causes spectrum overlook and thus spectrum opportunities are missed causing a degraded operation for the SUs. This tradeoff is tackled by means of defining a set of Grade-of-Service metrics which account for both the satisfaction level of PUs and SUs, and also on some aggregate satisfaction. In this way, performance results reveal that, by choosing an appropriate sensing operating point (Θ), the aggregate GoS can be minimized thus improving PU and SU perceived service quality. Moreover, the suitable operating point can be adjusted according to the current traffic load conditions and sensing periodicity cycles leading to an overall improved primary/secondary operation.

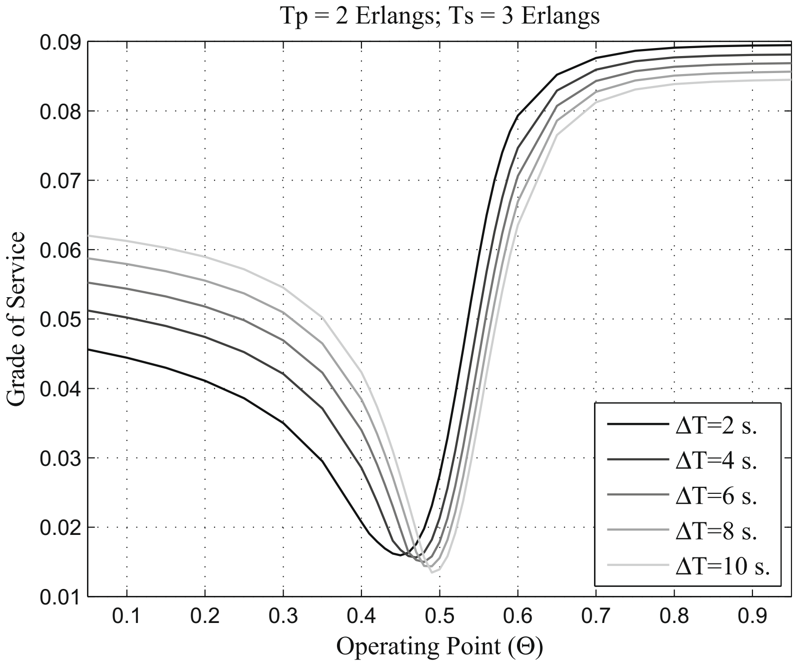

Fig. 7. Grade-of-Service (GoS) as a function of the operating point for different sensing periodicities.

References

[1] I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, S. Mohanty, NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey, Computer Networks 50 (13) (2006) 2127–2159, doi:http://dx.doi.org/10.1016/j.comnet.2006.05.001.

[2] S. Haykin, Cognitive radio: brain-empowered wireless communications, selected areas in communications, IEEE Journal 23 (2) (2005) 201–220, doi:10.1109/JSAC.2004.839380.

[3] Q. Zhao, B.M. Sadler, A survey of dynamic spectrum access, Signal Processing Magazine, IEEE 24 (3) (2007) 79–89.

[4] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, J. Evans, Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum, in: Sixth IEEE International Symposium, World of Wireless Mobile and Multimedia Networks (WoWMoM), 2005, pp. 78–85, doi:10.1109/WOWMOM.2005.36.

[5] S. Panichpapiboon, J.M. Peha, Providing secondary access to licensed spectrum through coordination, Wireless Networks 14 (3) (2008) 295–307, doi:http://dx.doi.org/10.1007/s11276-006-9415-8.

[6] P. Cordier et al., E2R cognitive pilot channel concept, in: IST Summit, Mykonos, 2007.

[7] J. Pérez-Romero, O. Sallent, R. Agustí, L. Giupponi, A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation, in: DySPAN'07, 2007, pp. 46–54, doi:10.1109/DYSPAN.2007.14.

[8] D. Cabric, S. Mishra, R. Brodersen, Implementation issues in spectrum sensing for cognitive radios, Signals, in: Conference Record of the Thirty-Eighth Asilomar Conference, Systems and Computers, vol. 1, 2004, pp. 772–776, doi:10.1109/ACSSC.2004.1399240.

[9] Q. Zhao, L. Tong, A. Swami, Y. Chen, Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: a POMDP framework, IEEE Journal on Selected Areas in Communications 25 (3) (2007) 589–600, doi:10.1109/JSAC.2007.070409.

[10] X. Liu, S. Shankar, Sensing-based opportunistic channel access, Mobile Networks and Applications 11 (4) (2006) 577–591, doi:http://dx.doi.org/10.1007/s11036-006-7323-x.

[11] Q. Zhao, S. Geirhofer, L. Tong, B. Sadler, Optimal dynamic spectrum access via periodic channel sensing, in: Wireless Communications and Networking Conference (WCNC), IEEE, 2007, pp. 33–37, doi:10.1109/WCNC.2007.12.

[12] D. Cabric, A. Tkachenko, R. Brodersen, Spectrum sensing measurements of pilot, energy, and collaborative detection, Military Communications Conference (MILCOM), 2006, pp. 1–7, doi:10.1109/MILCOM.2006.301994.

[13] L.S. Xiaorong Zhu, T.-S.P. Yum, Analysis of cognitive radio spectrum access with optimal channel reservation, IEEE Communications Letters 11 (4) (2007) 304–306.

[14] M. Raspopovic, C. Thompson, Finite population model for performance evaluation between narrowband and wideband users in the shared radio spectrum, in: DySPAN'07, 2007, pp. 340–346, doi:10.1109/DYSPAN.2007.52.

[15] S. Tang, B. Mark, An analytical performance model of opportunistic spectrum access in a military environment, in: IEEE Wireless Communications and Networking Conference (WCNC'08), 2008, pp. 2681–2686, doi:10.1109/WCNC.2008.470.

[16] Y. Xing, R. Chandramouli, S. Mangold, S. Shankar, Dynamic spectrum access in open spectrum wireless networks, IEEE Journal on Selected Areas in Communications 24 (3) (2006) 626–637, doi:10.1109/JSAC.2005.862415.

[17] B. Wang, Z. Ji, K. Liu, Primary-prioritized markov approach for dynamic spectrum access, in: DySPAN'07, 2007, pp. 507–515, doi:10.1109/DYSPAN.2007.73.

[18] P.K. Tang, Y.H. Chew, L.C. Ong, F. Chin, On the grade-of-services in the sharing of radio spectrum, in: Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), Second International Conference, 2007, pp. 85–89, doi:10.1109/CROWNCOM.2007.4549777.

[19] D. Wong, A.T. Hoang, Y.-C. Liang, F. Chin, dynamic spectrum access with imperfect sensing in open spectrum wireless networks, in: WCNC'08, 2008, pp. 2765–2770, doi:10.1109/WCNC.2008.484.

[20] F. Digham, M.-S. Alouini, M. Simon, On the energy detection of unknown signals over fading channels, Communications ICC'03, IEEE International Conference, vol. 5, 2003, pp. 3575–3579, doi:10.1109/ICC.2003.1204119.

[21] A. Ghasemi, E. Sousa, Collaborative spectrum sensing for opportunistic access in fading environments, in: DySPAN'05, 2005, pp. 131–136, doi:10.1109/DYSPAN.2005.1542627.

[22] H. Zhen, H. Hai, L. Fei, Y. Guangxin, X. Daxiong, Dynamic channel allocation scheme for hybrid cognitive network, in: Anti-counterfeiting, Security, Identification, IEEE International Workshop, 2007, pp. 179–183, doi:10.1109/IWASID.2007.373722.

[23] D. Bertsekas, R. Gallager, Data Networks, Prentice-Hall, 1992.

[24] J. Zander, S.-L. Kim, Radio Resource Management for Wireless Networks, Artech House, Inc., Norwood, MA, USA, 2001.

[25] D. Mitra, J.A. Morrison, Erlang capacity and uniform approximations for shared unbuffered resources, IEEE/ACM Transactions on Networks 2 (6) (1994) 558–570, doi:http://dx.doi.org/10.1109/90.365417.

[26] W.-Y. Lee, I.F. Akyildiz, Optimal spectrum sensing framework for cognitive radio networks, wireless Communications, IEEE Transactions 7 (10) (2008) 3845–3857, doi:10.1109/T-WC.2008.070391.

[27] Y.-C. Liang, Y. Zeng, E. Peh, A.T. Hoang, Sensing-throughput tradeoff for cognitive radio networks, wireless communications, IEEE Transactions 7 (4) (2008) 1326–1337, doi:10.1109/TWC.2008.060869.

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