A Novel Framework for the Characterization of Dynamic Spectrum Access Scenarios

(Invited Paper)

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***Abstract*—An efficient and utmost utilization of radio spectrum resources has stimulated the introduction of what has been termed dynamic spectrum access methodologies and implementations. While the traditional approach has been based on licensed (or primary) spectrum access, this new communication paradigm enables an opportunistic secondary access to shared spectrum resources provided mutual interference is kept below predefined margins. In this paper we propose a novel and flexible framework so as to account for primary-secondary spectrum sharing scenarios. In this sense, the use of a Discrete Time Markov Chain (DTMC) model is suggested and further justified. Some illustrative results are provided and validated against a system-level simulator thus confirming the suitability of the proposed approach.**

I. Introduction

The key purpose of spectrum management is to maximise the value that society gains from the radio spectrum by allowing as many users as possible while ensuring that mutual interference between users remains at acceptable levels [1], [2]. One common approach in the past has been the definition of a licensed user granted with exclusive exploitation for a specific frequency. The licensee has the right to transmit on that frequency on a specific geographic position and for a specified time. There may also be a number of other rules coupled to the license (e.g. on out-of-band emissions). While it is relatively easy in this case to ensure that excessive interference does not occur, this approach is unlikely to achieve the objective to maximize the value of spectrum. Besides, some unlicensed spectrum bands have been typically allocated. While this model sets a minimum set of rules to access the spectrum and, hence, enables fast introduction of new technologies into the marketplace, there is no guarantee that signals will not be interfered. Thus, this approach is typically effective for low transmitted power levels (i.e. low range technologies) [3].

From an economical point of view, economists have long argued that market mechanisms should be applied to radio spectrum [4]. From the technology point of view, advances in recent years such as ultra-wideband (UWB) and cognitive radios enable other forms of spectrum access. Cognitive radios, as devices with the capabilities to be aware of actual transmissions across a wide bandwidth and to adapt their own transmissions to the characteristics of the spectrum, offer great potential of developing more advanced spectrum management approaches [5]. Additionally, the pervasive presence of positioning mechanisms in mobile equipments could be very advantageous for novel forms of spectrum access.

The proposition of the TV band Notice of Proposed Rule Making (NPRM) [6], allowing unlicensed radios to operate in the TV broadcast bands if no harmful interference is caused to incumbent services (i.e. TV receivers), was a first milestone allowing dynamic spectrum access mechanisms. In this approach, the ”secondary” users (SUs) will have to sense the spectrum to detect primary user (PU) or SU transmissions and should be able to adapt to the varying spectrum conditions, ensuring that the primary rights are preserved [7]. These events culminated in the creation of the IEEE 802.22, developing a cognitive radio-based physical and medium access control layer for use by unlicensed devices on a non-interfering basis in spectrum that is allocated to the TV broadcast service [8].

The primary-secondary (P-S) spectrum sharing can take the form of cooperation or coexistence. Cooperation means there is explicit communications and coordination between primary and secondary systems, and coexistence means there is none [9]. When sharing is based on coexistence, secondary devices are essentially invisible to the primary. Thus, all of the complexity of sharing is borne by the secondary and no changes to the primary system are needed. There can be different forms of coexistence, such as spectrum underlay (e.g. UWB) or spectrum overlay (e.g. opportunistic exploitation of white spaces in spatial-temporal domain sustained on spectrum sensing, coordination with peers and fast spectrum handover). As for cooperation, again different forms of P-S interactions are possible. For example, spatial-temporal white spaces that can be exploited by SUs can be signalled through e.g. on-demand CPC (Cognitive Pilot Channel) [10] properly adapted to secondary spectrum usage purposes.

Spectrum awareness is a key enabler for secondary usage

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of spectrum. Sensing of spectrum to determine its occupancy suffers from problems, such as the hidden terminal, the fact that transmissions below the noise threshold of the measuring equipment can occur and result undetected, etc. Characteristics of the primary user such as small scale (i.e. primary power not much greater than secondary power [11]) or low predictability of spatiotemporal primary usage will make more difficult secondary spectrum usage exploitation. Clearly, cooperative P-S approaches will greatly facilitate the knowledge about radio conditions in a given scenario. Instead, coexisting P-S approaches will push the functionalities related to spectrum awareness towards SUs through sensing. Different forms of spectrum awareness will also show different impacts in terms of infrastructure cost (e.g. related to a centralized database containing spectrum usage information, related to the need to broadcast spectrum usage over a geographical region, etc.), compatibility with legacy primary systems if modifications are required, need for positioning capabilities at SUs, cost of terminals, etc. [12].

In the abovementioned context, the use of Markov chains becomes an important aid in modeling dynamic access to shared spectrum resources. In this sense, a significant number of papers in the literature have been devoted to the characterization of such scenarios using Markov models as, e.g., in [13]–[18]. In [13], a Continuous Time Markov Chain (CTMC) model is presented to model spectrum access of primary (wideband) and secondary (narrowband) users over a partitioned spectrum bandwidth. In [14] and [15] a CTMC model is also provided for the opportunistic access of wideband and narrowband users. However, as a difference from [13], a finite population traffic model is used for the characterization of SUs. It is worthwhile noting that work in [13]–[15] disregards the effect of erroneous sensing on the secondary network side, i.e. a perfect knowledge on the activity of primary users is assumed. An attempt to introduce the impact of sensing errors is provided in [16], where a CTMC model is also considered and sensing information is available upon secondary user arrival. In [17], [18], CTMC models are used to characterize the interactions between PUs and SUs and random spectrum access protocols are proposed and evaluated.

In this work, a Markovian framework based on Discrete Time Markov Chains (DTMC) so as to evaluate the opportunistic spectrum access in a primary-secondary spectrum sharing scenario exposed to spectrum awareness errors is proposed. The basis of DTMC models relies on the fact that the system state is observed at discrete periodic time instants [19]. This is an essential difference with respect to most of the above-mentioned work, which assume CTMC models which, by definition, observe the system state upon PU/SU arrival and/or departure events [19].

Therefore, CTMC models implicitly assume that up-to-date spectrum occupancy information is made available in those particular time instants associated to PU/SU arrival and/or departure events. In turn, the proposed DTMC model presented in this paper decouples traffic generation processes from spectrum occupancy information up-dates, then providing higher flexibility and broader applicability to the analytical framework. In particular, the DTMC will assume that spectrum occupancy information is provided at discrete time instants with periodicity ΔT, which in turn rules the operation of the DTMC model. It is worth noting that the periodicity assumed in the model would suitably fit e.g. in spectrum awareness schemes based on channel sensing, where it is generally required that SUs must remain silent in order to detect PU activity. In this case, coordination among SUs can be efficiently achieved by periodic MAC-level mechanisms in order to devote some of the data transmission time for sensing.

The organization of the paper is as follows. Section II introduces the considered framework, its functionalities and operation. Section III presents the core of the proposed framework which is based on the DTMC model. Some illustrative results are provided in Section IV and concluding remarks are pointed out in Section V.

II. Proposed Framework

The considered system involves a Primary Network (PN), serving PUs, and a Secondary Network (SN), serving SUs. Both the PN and the SN may operate either in an infrastructure or infrastructure-less fashion, each option introducing specific implications into the model. In any case, it is assumed that each network (i.e. PN and SN respectively) implement efficient protocols for the correct and coordinated operation among their own users (i.e. PUs and SUs respectively). Thus, the PN is aware of the spectrum occupancy by PUs and, correspondingly, the SN is aware of the spectrum occupancy of SUs. The PN has been assigned a total number of C channels, partitioning a certain frequency band. SUs can make use of free channels; though PUs have strict priority over SUs (i.e. if a SU is using a given channel and this channel is required by a PU, then the SU must release it).

The procedure for the SN operation involves the next steps:

1) Identification of a specific channel to support SU communication.
2) Configuration of secondary transmit and receive ends to enable communication over the identified channel.
3) Detection of primary presence communication while maintaining the secondary communication, in which case the secondary communication must evacuate the channel. Spectrum handover (SpHO) mechanisms, if available, will intend to find a proper alternative channel where the communication can be continued in order to avoid the interruption of the secondary communication.

As mentioned, P-S implementation can be in the form of coexistence (i.e. there is no direct coordination mechanism between the PN and the SN) or coordination with a certain coupling degree between the PN and SN.

In the uncoordinated approach, the identification of a candidate frequency band for the secondary communication as well as the detection of primary's presence is performed, within the SN, based on sensing mechanisms without any direct interaction with PN. Channel occupancy detection performed at the SU's terminal side through sensing mechanisms is affected by a number of aspects (e.g. adverse channel conditions, hidden terminal problem, limited sensitivity on the sensing equipment, etc.) that may limit the reliability of sensing results [20]. Typically, spectrum detection through sensing in the presence of errors performs a binary hypotheses test over a given band (or channel): $\mathcal{H}_0$ if the channel is available and $\mathcal{H}_1$ if the channel is occupied. Accordingly, the miss-detection and false-alarm probabilities, δ and ε can be defined as:

$$\varepsilon = \Pr\left[\mathcal{H}_1 | \mathcal{H}_0 \text{ is true}\right] \quad \delta = \Pr\left[\mathcal{H}_0 | \mathcal{H}_1 \text{ is true}\right] \qquad (1)$$

where δ and ε depend on the so-called time-bandwidth product, defined as $m = T \cdot W$, with T the time devoted to sense bandwidth W [20]. In general, the longer we sense the bandwidth W seeking for spectrum opportunities the more reliable are our sensing measures (i.e. lower δ and ε values), however, high T values, will trade-off the achievable throughput of SUs [21]. As for the availability of updated primary spectrum occupancy information based on sensing, the parameter ΔT would represent the time between two consecutive sensing information updates. Considering that sensing procedures requires some time, $T_{sens} = C \cdot T$ (i.e. assuming sequential channel sensing), and that the longer we sense the more accurate spectrum occupancy information becomes, the value of $T_{sens}/\Delta T$ which provides a measure of sensing efficiency must be carefully chosen.

In the coordinated approach, the identification of a candidate frequency band for the secondary communication as well as the detection of PU presence is supported through the availability of a CPC, which informs SUs about channel occupancy on the PN. Similar to the sensing case, it is assumed that channel occupancy information will be affected by miss-detection and false-alarm probabilities, δ and ε. In this case, the parameters δ and ε would be related to errors into the information conveyed by the CPC (e.g. limited reliability in supporting databases containing radio environment characterization, non up-to-date information about primary's activity, etc.). As for the availability of updated primary spectrum occupancy information, in this case the parameter ΔT would represent the time between two consecutive channel occupancy information updates provided by the CPC.

Fig. 1 shows the block diagram of the proposed modeling framework mainly consisting of three blocks: the implementation and functionalities block, the spectrum awareness block and, finally, the DTMC block from which spectrum occupancy performance measures can be extracted. According to the chosen P-S implementation approach, i.e. coordinated or uncoordinated, the implementation and functionalities block in Fig. 1 will provide, among others, appropriate values for primary detection parameters δ and ε.

As for the spectrum awareness block, it provides statistical spectrum occupancy information through parameter $b_{(k,i)}$ which is the conditional probability that k PUs have been detected given that actually i PUs are in the system. So as to obtain $b_{(k,i)}$, the spectrum awareness block is fed by δ and ε so as to account for possible detection errors.

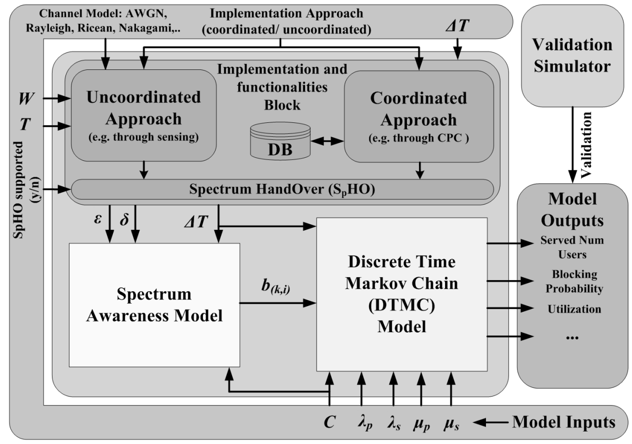

Fig. 1. Block diagram of the generic framework.

Finally, the DTMC model constitutes the core block and it is devoted to determine the statistical occupancy of the shared spectrum by PUs and SUs. It is mainly fed by traffic-related arrival and departure rates (λ_p and λ_s along with μ_p and μ_s for PUs and SUs correspondingly), and also the number of channels to be shared, C. This block is also fed by $b_{(k,i)}$ and by input parameter ΔT, which denotes the periodic time instants in which updated spectrum occupancy information is made available for secondary communication, which is, on the other hand, the operating time-basis of the DTMC model.

Then, the presented model is generic enough to characterize a wide range of implementation aspects and configuration alternatives into the primary/secondary systems and, therefore, offers a wide applicability.

III. 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 W is partitioned into a total amount of C channels (bands) which are available for both PUs and SUs. It is further assumed that both PUs and SUs demand a single channel for transmission purposes. In a DTMC we observe the system state at discrete time instants $\{t_0, t_1, t_2, ..., t_n, ...\}$, with $t_n = t_0 + n \cdot \Delta T$ and periodicity ΔT, which is assumed to specify the time instants where primary spectrum occupancy information is made available for secondary communication use. Let $I_n = (t_n, t_{n+1}]$ define the *n-th* time interval between two successive observation times. The DTMC model definition involves a number of steps described in the following.

A. State Space Definition

Let $N_p(t_n)$ and $N_s(t_n)$ be stochastic processes representing 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. For a correct spectrum use (i.e. with no collisions), the state space $\mathcal{S}$ must account for the number of feasible states, $S_{(i,j)}$, provided that the number of PUs (i) plus SUs (j) does not exceed the total number of available channels (C). However, in the presence of spectrum detection errors, a SU might be erroneously assigned to a band already in use by a PU. Therefore, the considered state space $\mathcal{S}$ must contain all possible sates $S_{(i,j)}$ which fulfill both $i \leq C$ and $j \leq C$, formally, $\mathcal{S} = \{S_{(i,j)} : i \leq C, j \leq C\}$.

B. Detection of Primary Spectrum Occupancy

At a particular time t_n, let the state of the DTMC be $\mathbf{X}_n = S_{(i,j)} \in \mathcal{S}$. At this same time instant, 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 $\mathbf{Y}_n = S_{(k,j)} \in \mathcal{S}$, 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). Consequently, we are interested in determining the probability:

$$b_{(k,i)} = \Pr[\mathbf{Y}_n = S_{(k,j)} | \mathbf{X}_n = S_{(i,j)}] \tag{2}$$

i.e., the probability of detecting k PUs when there are in fact i PUs in the system at time t_n. Thus, the statistical PU spectrum occupancy distribution at time t_n provided by (2) will be used by the SN to assign/de-assign SUs accordingly.

C. Arrival and Departure Processes

Let $N^A \in \{N^{PA}, N^{SA}\}$ along with $N^D \in \{N^{PD}, N^{SD}\}$ denote the number of arrivals and departures of PUs and SUs respectively in I_n.

Given PUs and SUs arrive to 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 [19]:

$$P_k^A = \Pr[N^A = k] = \left[(\lambda\Delta T)^k / k!\right] e^{-\lambda\Delta T} \tag{3}$$

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 rate μ, the probability of a session departure in I_n is [19]:

$$P^D = 1 - e^{-\mu\Delta T} \tag{4}$$

Then, the probability of having k-out-of-m departures in I_n, P_k^D, is given by the binomial distribution [19]:

$$P_k^D = \Pr[N^D = k] = \binom{m}{k} (1 - e^{-\mu\Delta T})^k (e^{-\mu\Delta T})^{m-k} \tag{5}$$

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

D. Channel Assignment and De-assignment Processes

The number of PU/SU spectrum assignments and de-assignments in I_n, $N_a \in \{N_a^P, N_a^S\}$ and $N_d \in \{N_d^P, N_d^S\}$, 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. In the following, the expressions for the spectrum assignment and de-assignment probabilities in I_n are derived.

1) Primary Users: Let $\mathbf{X}_n = S_{(i,j)}$, the probability of assigning k PUs in I_n given we have $l \leq i$ PU de-assignments in I_n, will depend on the number of PU arrivals in I_n as:

$$\begin{aligned} a^P_{(i,j,k,l)} &= \Pr[N_a^P = k | \mathbf{X}_n = S_{(i,j)}, N_d^P = l] \\ &= \begin{cases} \Pr[N^{PA} = k] = P_k^{PA}, & \text{if } i - l + k < C \\ \Pr[N^{PA} \geq k] = 1 - \sum\limits_{m=0}^{k-1} P_m^{PA}, & \text{if } i - l + k = C \end{cases} \end{aligned} \tag{6}$$

Let $\mathbf{X}_n = S_{(i,j)}$, the probability of de-assigning k SUs in I_n, with $0 \leq k \leq i$, depends on the number of PU departures in I_n:

$$d^P_{(i,j,k)} = \Pr[N_d^P = k | \mathbf{X}_n = S_{(i,j)}] = \Pr[N^{PD} = k] = P_k^{PD} \tag{7}$$

2) Secondary Users: In $\mathbf{X}_n = S_{(i,j)}$, the probability of assigning k SUs in I_n, with $0 < k \leq C - i - j + l$, given we have $l \leq j$ SU de-assignments in I_n, will depend on the detected state at t_n, $\mathbf{Y}_n = S_{(m,j)}$, and on the number of SU arrivals as:

$$\begin{aligned} a^S_{(i,j,k,l)} &= \Pr[N_a^S = k | \mathbf{X}_n = S_{(i,j)}, N_d^S = l] \\ &= \sum_{m=0}^{C-k-j+l} \Pr[N_a^S = k | Y_n = S_{(m,j)}, N_d^S = l] \cdot b_{(m,i)} \\ &= \sum_{m=0}^{C-k-j+l} \bar{a}^S_{(m,j,k,l)} \cdot b_{(m,i)} \end{aligned} \tag{8}$$

with, similar to (6),

$$\bar{a}^S_{(m,j,k,l)} = \begin{cases} P_k^{SA}, & \text{if } m + j - l + k < C \\ 1 - \sum\limits_{r=0}^{k-1} P_r^{SA}, & \text{if } m + j - l + k = C \end{cases} \tag{9}$$

For $k = 0$, we have

$$\begin{aligned} a^S_{(i,j,k,l)} &= \Pr[N_a^S = k | \mathbf{X}_n = S_{(i,j)}, N_d^S = l] \\ &= \sum_{m=0}^{C-k-j+l} \bar{a}^S_{(m,j,k,l)} \cdot b_{(m,i)} + \sum_{m=C-j+l}^{C} b_{(m,i)} \end{aligned} \tag{10}$$

Let $\mathbf{X}_n = S_{(i,j)}$, the probability of de-assigning exactly k SUs (with $0 \leq k \leq j$) in I_n will depend on the detected state at t_n, $\mathbf{Y}_n = S_{(m,j)}$, but also on the session departure probability of SUs. Let $N_d^{S,S}$ and $N_d^{S,SC}$ denote the number of de-assignments due to spectrum detection and due to service completion respectively. The probability of de-assigning k SUs in I_n due to detection of state $\mathbf{Y}_n = S_{(m,j)}$ is given by:

$$\begin{aligned} &\Pr[N_d^{S,S} = k | \mathbf{X}_n = S_{(i,j)}, N_d^{S,SC} = l] \\ &\qquad = \Pr[m + j - l = C + k] = b_{(C+k-j+l,i)} \end{aligned} \tag{11}$$

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

$$\Pr[N_d^{S,S} = 0 | \mathbf{X}_n = S_{(i,j)}, N_d^{S,SC} = l] = 1 - \sum_{k=1}^{j-l} b_{(C+k-j+l,i)} \tag{12}$$

Then, from (11) and (12), we may write

$$d^{S,S}_{(i,j,k,l)} = \Pr[N^{S,S}_d = k | \mathbf{X}_n = S_{(i,j)}, N^{S,SC}_d = l] = \begin{cases} b_{(C+k-j+l,i)} & \text{if } 0 < k \leq j-l \\ 1 - \sum_{r=1}^{j-l} b_{(C+r-j+l,i)} & \text{if } k = 0 \end{cases} \quad (13)$$

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

$$d^{S,SC}_{(i,j,k)} = \Pr[N^{S,SC}_d = k | \mathbf{X}_n = S_{(i,j)}] = \Pr[N^{SD} = k] = P^{SD}_k \quad (14)$$

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:

$$d^{S}_{(i,j,k)} = \Pr[N^{S}_d = k | \mathbf{X}_n = S_{(i,j)}] = \sum_{r=0}^{k} d^{S,S}_{(i,j,k-r,r)} \cdot d^{S,SC}_{(i,j,r)} \quad (15)$$

E. Transition Probabilities

The transition probabilities between each pair of states $S_{(k,l)} \rightarrow S_{(i,j)}$ in our DTMC model can be expressed as [19]:

$$P_{(i,j|k,l)} = \Pr[X_{n+1} = S_{(i,j)} | X_n = S_{(k,l)}] = \Pr[N_p(t_{n+1}) = i | N_p(t_n) = k] \cdot \Pr[N_s(t_{n+1}) = j | N_s(t_n) = l] \quad (16)$$

where the mutual independence of processes $N_p(t_n)$ and $N_s(t_n)$ has been assumed. Probabilities $P_{(i,j|k,l)}$ are the entries of the transition probability matrix $\mathbf{P}$, from which the steady state probabilities of the DTMC will be computed [19].

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

$$P_{(i+N,j+M|i,j)} = \left(\sum_{k=\max(-N,0)}^{i} a^{P}_{(i,j,N+k,k)} \cdot d^{P}_{(i,j,k)} \right) \cdot \left(\sum_{k=\max(-M,0)}^{j} a^{S}_{(i,j,M+k,k)} \cdot d^{S}_{(i,j,k)} \right) \quad (17)$$

with parameters in (17) previously defined in section III-D.

IV. Illustrative Results

We consider the total bandwidth partitioned into C=16 channels. The offered primary traffic load is fixed with value $T_p = \lambda_p / \mu_p = 10$ Erlangs (note that a high primary load is consequently assumed). We further assume that spectrum occupancy distribution $b_{(k,i)}$ in (2) is obtained through *offline* snapshot simulation with values of $\delta = \varepsilon = \{0, 0.01, 0.3\}$, where it should be noted that $\delta = \varepsilon = 0$ indicates perfect (error-free) detection. Spectrum occupancy information periodicity is, unless otherwise stated, $\Delta T = 0.1$ seconds. Performance metrics, described in the following subsection, are plotted against several offered secondary traffic load $T_s = \lambda_s / \mu_s$ values.

A. Performance Metrics

From the resulting transition probability matrix $\mathbf{P}$ defined in (17), we obtain the true steady state probabilities, $P_{(i,j)} = \lim_{n\rightarrow\infty} \Pr\left[\mathbf{X}_n = S_{(i,j)}\right]$, for each true state $S_{(i,j)}$ in the state space $\mathcal{S}$. The knowledge of such statistical distribution enables the definition of several performance metrics which is addressed in the following. On the other hand, it is also relevant to determine the steady state probabilities of the detected states (i.e. including possible sensing errors): $P'_{(i,j)} = \lim_{n\rightarrow\infty} \Pr\left[\mathbf{Y}_n = S_{(i,j)}\right]$, which are computed as:

$$P'_{(i,j)} = \sum_{n=0}^{C} b_{(i,n)} \cdot P_{(n,j)} \quad (18)$$

The fraction of assigned channels, C_f, is defined as the probability that all channels are occupied, thus:

$$C_f = C^{-1} \cdot \sum_{S_{(i,j)} \in \mathcal{S}} (i+j) \cdot P_{(i,j)} \quad (19)$$

Blocking occurs whenever a new user cannot be assigned a channel given all channels are occupied or thought to be occupied. Subsequently, blocking probability for PUs can be computed from the true steady state probabilities as:

$$P^P_B = \sum_{j=0}^{C} P_{(C,j)} \quad (20)$$

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

$$P^S_B = \sum_{i=0}^{C} \sum_{j=C-i}^{C} P'_{(i,j)} \quad (21)$$

The interference probability is defined as the probability of being in state $S_{(i,j)} \in \mathcal{S}_I$ with $\mathcal{S}_I = \left\{ S_{(i,j)} : i+j > C \right\}$, i.e. the probability that at least a channel is simultaneously occupied by both a PU and a SU, then:

$$P_I = \sum_{S_{(i,j)} \in \mathcal{S}_I} P_{(i,j)} \quad (22)$$

B. Results

Fig. 2 shows the fraction of assigned channels against the offered secondary traffic load for the considered values of δ and ε. As expected, the better the spectrum detection information (i.e. lower δ and ε values) the better spectrum opportunities can be exploited and thus higher secondary assignments are achieved.

Fig. 3 shows the blocking probability for both PUs and SUs. Given the offered primary traffic is constant, a constant blocking probability for PUs is observed, whereas for SUs, the better the spectrum detection information the higher the number of SUs are admitted thus potentially higher blocking situations may occur.

Finally, Fig. 4 shows the impact of spectrum occupancy information periodicity in terms of interference probability as defined in (22). Results indicate that high values of ΔT causes the secondary system to take decisions with out-of-date primary spectrum occupancy information which translates into higher interference probabilities.

It is worthwhile noticing that results obtained via the DTMC model have been validated against a system-level simulator. In this sense, Figs. 2-3 represent simulator results as circles, which, on the other hand, match those obtained via the DTMC.

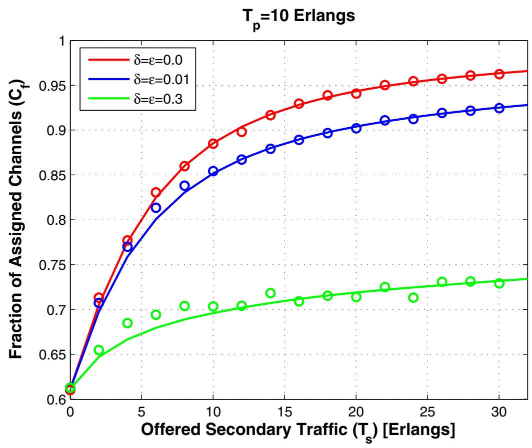

Fig. 2. Fraction of assigned channels.

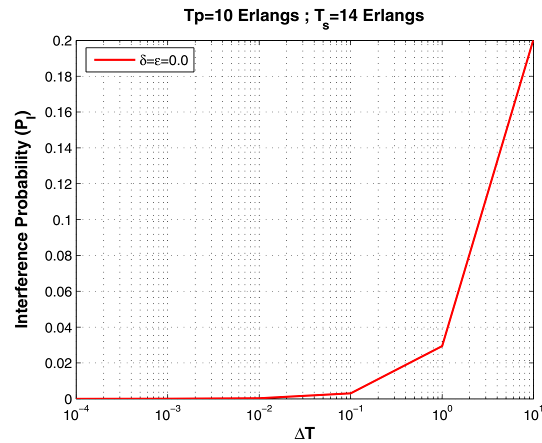

Fig. 4. Interference probability against ΔT.

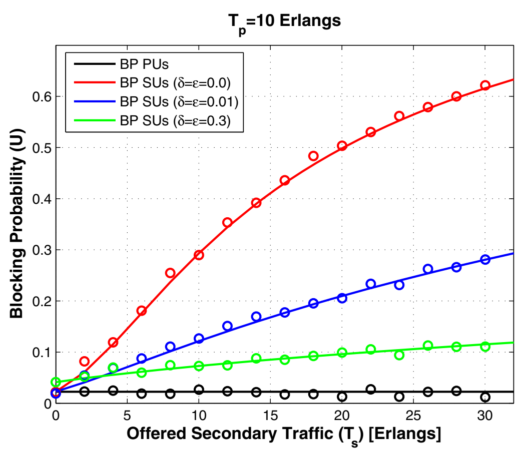

Fig. 3. Blocking probability of PUs and SUs.

V. Conclusion

In this work a generalized and flexible framework for the definition and evaluation of opportunistic shared spectrum scenarios has been presented. This framework is capable of supporting a wide range of implementation possibilities and functionalities. In this sense, the suitability of a DTMC model as the core of the framework has been suggested and further justified. The DTMC model has been formulated with a high degree of generality and some performance metrics extracted. The model has been validated against a system-level simulator and some illustrative results presented and commented. This framework enables future work to be carried out in multiple directions so as to account for the large amount of intrinsic problems related to these types of scenarios.

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