Flexible Spectrum Access for Opportunistic Secondary Operation in Cognitive Radio Networks

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***Abstract*—In this letter a Discrete-Time Markov Chain (DTMC) framework is adopted to capture the effect of flexible spectrum channelization for the opportunistic access of secondary users (SUs) in a primary-secondary shared spectrum scenario. Two implementation alternatives are proposed: a fixed channelization scheme (FCS) and an adaptive channelization scheme (ACS). Moreover, service-type characterization of SUs is also addressed by defining time vs. volume based services. Results indicate the suitability of the ACS over the FCS.**

***Index Terms*—Cognitive radio, dynamic spectrum access, discrete time Markov chains, performance evaluation.**

I. INTRODUCTION

THE concept of opportunistic spectrum access (OSA) arises to enable the utmost and efficient utilization of valuable spectrum resources. In this framework, the notion of spectrum sharing among primary users (PUs) with exclusive spectrum rights, and secondary users (SUs), which may access the shared spectrum in a non-interfering basis, has been the subject of many research efforts, see e.g. [1]–[3].

In this work we are concerned with the problem of OSA considering the Hierarchical Access Model [2], where the licensed (or primary) spectrum is opened to SUs provided the interference over the PUs is kept under acceptable limits. Specifically, the spectrum overlay case is adopted where temporal spectrum holes are targeted in order to allow SUs to identify and exploit them in a non-intrusive way. Accordingly, spectrum awareness mechanisms are implemented on the secondary network (SN) side in order to detect the utilized primary spectrum at a given time. Spectrum awareness by means of spectrum sensing mechanisms is adopted [4]. In this case, SUs may be equipped with sensors reporting spectrum occupancy measurements to a centralized SN entity which will then regulate the use of spectrum accordingly.

A common abstraction for spectrum resources in a shared spectrum environment consists of a given frequency band partitioned into a number of channels, see e.g. [5]–[7]. Then, it is necessary to ensure that a given channel is not accessed by both a PU and a SU at the same time, thus causing mutual interference. According to the spectrum partition sizes devoted to PUs and SUs in a spectrum sharing system, users may be categorized in wide band (WB) access users as opposed to narrow band (NB) access users. While [5]–[7] presents different co-existence cases between WB and NB PUs and SUs, work therein solely applies for the considered specific partition cases, thus exhibiting limited applicability. To this respect, this letter explores several alternatives for the partition, or channelization, of available spectrum in order to provide an efficient access and spectrum utilization for both PUs and SUs. Specifically, a Fixed Channelization Scheme (FCS) and an Adaptive Channelization Scheme (ACS) are proposed as two possible OSA mechanisms for SUs. The FCS partitions the whole spectrum bandwidth in a number of fixed channels for both PUs and SUs. As opposed to [5]–[7], where specific models accounted for particular WB-NB cases between PUs and SUs, the FCS presented herein allows to define the entire set of WB vs. NB cases between PUs and SUs, thus exhibiting an improved applicability and scope. To the best of the author's knowledge, only [8] describes a similar approach where the channelization values for PUs and SUs can be adjusted. Moreover, the proposed ACS is able to adapt the channelization value of SUs according to current traffic demands of both PUs and SUs, thus exhibiting a higher flexibility as compared to both the FCS and the model in [8].

This letter also considers the characterization of SU services by adopting two types of requests. Firstly, Time-Based Services (TBSs) aim for the use of a particular amount of bandwidth for a given time, regardless of the allocated bitrate. Examples of TBSs are real-time (RT) traffic such as voice calls, video-calls, RT video-streaming, etc. where the session duration can be considered independent from the allocated bitrate if minimum QoS requirements are met. Secondly, Volume-Based Services (VBSs) aim at transmitting a given amount of data, hence the service duration depends on the achievable bitrate, i.e. on the amount of assigned spectrum bandwidth. File bulk transfer, e-mail, web access, etc. are examples of VBSs. This SU service characterization also constitutes a major contribution with respect to existing works which usually assume the TBS case (see, e.g., [5]–[8]). In this letter, the use of the aforementioned channelization schemes when different SU service characterizations apply is explored. To accomplish this task, we rely on a Markov model previously introduced by the authors in [9] and adapt it to include the aforementioned channelization and service models.

The use of Markov models to depict the behavior of dynamic access to shared spectrum resources has been addressed in recent literature, see e.g. [5]–[8]. In [5] (along with amendments in [10]), a continuous time Markov chain (CTMC) model is used to describe the spectrum access of WB PUs and NB SUs over a partitioned spectrum bandwidth. In [6], [7] a CTMC model is also used for the OSA of WB

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SUs and NB PUs in [6], and equal-band PUs and SUs in [7]. Noteworthy, work in [5]–[7] disregards the effect of erroneous sensing on the SN side, i.e. a perfect knowledge on the PU activity is assumed. An attempt to introduce the impact of sensing errors is provided in [8], where a CTMC model is also considered and sensing information is available upon SU arrival. However, sensing errors in [8] are not related to any particular spectrum sensing mechanism implementation. Conversely, as reflected in [9], spectrum sensing errors in the proposed model are adopted from well-known expressions regarding the energy detection of signals in Rayleigh fading as in [11], hence achieving higher modeling accuracy.

This letter is organized as follows. Section II describes the spectrum channelization schemes FCS and ACS along with service types TBS and VBS. Section III presents the DTMC model along with the channelization and service type descriptions, extending the work in [9]. Performance metrics and results are addressed in section IV whereas conclusions are given in section V.

II. Spectrum Access Model

The considered scenario is that of an infrastructure-based primary network (PN), where the primary base station (BS) provides connectivity to PUs. The PN has a prioritized use of the available spectrum band W_T where channels are assigned to PUs. Alongside, a secondary infrastructure-based network provides connectivity to SUs through the opportunistic use of unoccupied spectrum. We are concerned with the case where PUs and SUs coexist in an area with coverage of both the PN and the SN.

A. Spectrum Channelization

The PN partitions the whole spectrum into M_p channels, whereas the SN may consider a spectrum channelization of M_s. The SN could decide the most appropriate value of M_s according to the network status or SU service characteristics at a given time. Fig. 1 shows the spectrum channelization concept. Note that, with one SU accessing the shared spectrum and with $M_s = \{16, 12, 8\}$ [Figs. 1(a), 1(b) and 1(c)] spectrum usage is not maximized, while this is true for $M_s = 4$ [Fig. 1(d)]. Moreover, with one SU and three PUs, if $M_s = 2$ or $M_s = 1$ [Fig. 1(e) and Fig. 1(f)], non-harmful SU access is not possible.

For the sake of algebra tractability, the next assumption is considered:

(A1) $M_s/M_p \in \mathbb{Z}$ provided $M_s \geq M_p$ and $M_p/M_s \in \mathbb{Z}$ for the case of $M_p \geq M_s$,

meaning that subchannels are always an integer fraction of a channel. Furthermore, it is assumed that

(A2) primary channelization is given by $M_p = 2^n$, for $n > 0$;

(A3) secondary channelization is given by $M_s = 2^m$ for $M_p \geq M_s$ $(m = 0, 1, 2...)$, and $M_s = m \cdot M_p$ for $M_s \geq M_p$ $(m = 1, 2, ...)$ with $M_s \leq M_{s,max}$ accounting for minimum spectrum requirements.

Note that both (A2) and (A3) fulfill assumption (A1). Additionally, it should be noted that assumption (A1), besides

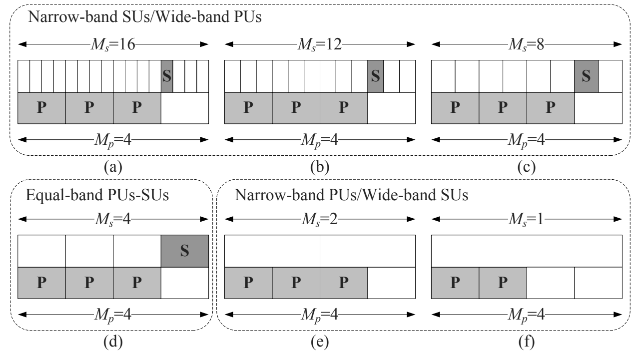

Fig. 1. Spectrum channelization model given by M_p and M_s.

ensuring algebra tractability, leads to improved spectrum use since it prevents partial channel overlapping between PUs and SUs caused when (A1) is disregarded.

For convenience, we define the set of secondary channelization values as $\mathcal{M}_s$. In the example layout in Fig. 1, we have that $\mathcal{M}_s = \{1, 2, 4, 8, 12, 16\}$ where it has been assumed that $M_{s,max} = 16$.

The secondary BS (SBS) will notify SUs about the value of M_s using appropriate signaling channels. Two schemes are proposed according to the interaction degree between the SBS and the SUs. First, a *fixed channelization scheme* (FCS) is considered, by which the value of M_s is updated and signaled to the SUs once or, alternatively, at very large time-scales. Second, an *adaptive channelization scheme* (ACS) is defined where M_s is constantly adjusted so as to maximize the spectrum utilization, defined later on.

Since secondary spectrum resources are varied according to the value of M_s, the SU throughput R_s (in bits-per-second, bps) will vary accordingly. Indeed, Shannon's capacity expression enables writing:

$$R_s = (W_T/M_s) \log_2 (1 + \gamma), \quad (1)$$

where γ is the signal-to-noise ratio affecting the SU. According to (1), a high spectrum partition (i.e. large M_s values) will cause a higher SU admittance in the system at the cost of reduced throughput. Conversely, small M_s values imply increased throughput at the expense of reduced SU admittance.

Lastly, it is assumed that the SN knows the value of the primary channelization, M_p, which, moreover, will be assumed to have a fixed value.

B. Secondary User Service Type Characterization

Inspired by [12], [13], two different SU service types are considered according to the holding time characteristics when accessing the shared spectrum. First, a *time-based service* (TBS) is considered, where a specific SU demands spectrum access during some given time regardless of the granted throughput R_s. This could be the case of a constant bit rate (CBR) service, or a variable bit rate (VBR) service, such as e.g. a video streaming service, where an increased throughput would mean an improved perceived QoS without affecting the duration of the service. Secondly, we consider a *volume-based service* (VBS) where a specific SU intends to transmit some data bulk. Accordingly, the holding time of this user will depend on the achievable throughput. As for PUs, it is assumed that they solely demand TBS.

III. Discrete-Time Markov Model

The presented model departs from [9] where the authors addressed the limited case of $M_p = M_s \triangleq C$. In this letter, we extend the expressions in [9] to capture the FCS and ACS for TBS and VBS.

A. State Space Definition

In a DTMC the system state is observed at discrete time instants $\{t_0, t_1, ..., t_n, ...\}$, with $t_n = t_0 + n \cdot \Delta T$ and periodicity ΔT, which also specifies the sensing periodicity. In addition, let $I_n = (t_n, t_{n+1}]$ define the *n-th* time interval between two successive observation times. If $N_p(t_n)$ and $N_s(t_n)$ are stochastic processes indicative of 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. The *state space* will specify those feasible or infeasible states in the DTMC model depending on the adopted channelization scheme.

1) Fixed Channelization Scheme (FCS): The FCS mainly adopts the state space definition provided in [9, §3.1] for $M_p = M_s \triangleq C$. Hence, equivalent definitions to those in [9] for the state space, $\mathcal{S}$, the collision state space, $\mathcal{S}_c$, and the possible collision state space, $\mathcal{S}_{pc}$, are briefly outlined regarding the general case $M_p \neq M_s$ as:

$$\mathcal{S} = \{S_{(i,j)} : 0 \le i \le M_p, 0 \le j \le M_s\}, \tag{2}$$

$$\mathcal{S}_c = \{S_{(i,j)} : i/M_p + j/M_s > 1\} \subset \mathcal{S}, \tag{3}$$

$$\mathcal{S}_{pc} = \{S_{(i,j)} : i/M_p + j/M_s \le 1, j > 0, i > 0\} \subset \mathcal{S}. \tag{4}$$

As for the non-collision state space ($\mathcal{S}_{nc}$), it is given directly by [9, eq. (9)].

2) Adaptive Channelization Scheme (ACS): In this case, M_s will vary according to spectrum occupation measures. It is further assumed that $0 \le M_s \le M_{s,max}$, where $M_{s,max}$ is a design parameter. Then, the state space $\mathcal{S}$ is the set of states such that

$$\mathcal{S} = \{S_{(i,j)} : 0 \le i \le M_p, 0 \le j \le M_{s,max}\}, \tag{5}$$

where, analogously to the FCS case in Section III-A1, the set of states implying collision is defined as

$$\mathcal{S}_c = \{S_{(i,j)} : i/M_p + j/M_{s,max} > 1\} \subset \mathcal{S}, \tag{6}$$

along with those states possibly implying a spectrum collision, i.e.

$$\mathcal{S}_{pc} = \{S_{(i,j)} : i/M_p + j/M_{s,max} \le 1, j > 0, i > 0\} \subset \mathcal{S}. \tag{7}$$

As for the non-collision state space $\mathcal{S}_{nc}$, it is directly given by [9, eq. (9)].

B. Spectrum Awareness Model

So as to consider spectrum sensing errors in the form of false-alarm and missed-detection probabilities, ε and δ respectively, the probabilistic model derived in [9, eq. (11)] is adopted. This model provides the conditioned probability, $b_{(k,i)}$, of sensing k PUs when there are actually i PUs at time t_n. Channelization value C in [9, eq. (11)] should be replaced by M_p to specifically account for the PU channelization.

C. Channelization Scheme

According to the chosen channelization scheme, i.e. FCS or ACS, the value of M_s will be different. While for the FCS, SU channelization is simply a constant value, $M_s(i,j) = M_s$, in the ACS case M_s will vary depending on the state $S_{(i,j)}$. The aim is in finding the minimum value of M_s (which implies higher spectrum occupation and, thus higher throughput) such that the spectrum utilization is maximized. In particular, we focus on those values of M_s belonging to the set $\mathcal{M}_s$:

$$M_s(i,j) = \underset{M_s \in \mathcal{M}_s}{\arg\max} [U(i,j)], \tag{8}$$

with $U(i,j) = i/M_p + j/M_s$ the spectrum utilization and where M_p is assumed a known input parameter.

Expression (8) guarantees that the utmost spectrum utilization is fairly achieved among all SUs. However, since the SN will select the channelization value and it is not aware of the "true" number of PUs (i) but rather on the number of sensed PUs (m), it will be able to compute $M_s(m,j)$ instead of $M_s(i,j)$. Therefore, sensing errors will affect the channelization adjustment process.

D. Secondary Service Characterization

For TBS, the service-time distribution is given by the exponentially distributed service rate with average duration $1/\mu_s$. Consequently, the service departure rate in state $S_{(i,j)}$ is given by $\mu_s(i,j) = j \cdot \mu_s$ [14].

For the VBS, the average service-time of a SU will depend on the data volume to be transmitted (L), which is assumed to be exponentially distributed, and on the achieved data-rate (R_s) as:

$$\begin{aligned} \frac{1}{\mu_s} &= \frac{E[L]}{R_s \cdot \eta_{sens}} \\ &= \frac{E[L]}{\eta_{sens} \cdot [W_T/M_s(i,j)] \cdot \log_2(1+\gamma)} \triangleq \frac{M_s(i,j)}{\mu_T}, \end{aligned} \tag{9}$$

where (1) has been used and $1/\mu_T$ is defined as the average service-time when a single SU accesses the full spectrum W_T. Moreover, SU bit-rate is affected by the sensing efficiency $\eta_{sens} \in [0,1]$ given in [9, eq. (4)], denoting the fraction of time devoted to sensing tasks while not contributing to data delivery. Hence, the service departure rate in state $S_{(i,j)}$ yields $\mu_s(i,j) = \mu_T / M_s(i,j)$, indicating that the service rate is lessened when increasing channelization M_s. Note that the value of M_s will depend on the adopted channelization scheme, i.e. $M_s(i,j) = M_s$ for the FCS, and $M_s(i,j)$ in (8) for the ACS.

E. Arrival and Departure Processes

Assuming PUs (SUs) arrive to the system following a Poisson distribution, the probability that k PU (SU) arrivals occur in I_n, P_k^{PA} (P_k^{SA}), is given by [9, eq. (12)] for $\lambda = \lambda_p$ ($\lambda = \lambda_s$). If the session duration of PUs (SUs) is exponentially distributed, the probability of having k-out-of-m PU (SU) departures in I_n, P_k^{PD} (P_k^{SD}), is given by [9, eq. (14)] for $\mu = \mu_p$ ($\mu = \mu_s$). Specifically for the secondary departure rates, and according to the defined services TBS and VBS, the value of μ_s will be different in each case. For the TBS, μ_s is a constant value regarded as an input parameter. On the other hand, for the VBS, $\mu_s = \mu_s(i,j) = \mu_T/M_s(i,j)$ where if the FCS is applied then $M_s(i,j) = M_s$, and if the ACS is adopted then $M_s(i,j)$ is given in (8).

For the sake of algebra tractability, the same hypotheses as in [9] are assumed: 1) not allowing a session arriving in I_n to depart in this same I_n; and 2) disregarding the order in which session arrivals and departures occur in a given I_n. The applicability range of both these hypothesis was assessed and validated against a system level simulator in [9] to which the interested reader is referred.

F. State Transition Probabilities

Departing from expressions in [9] for the case of $M_p = M_s \triangleq C$, this section extends them to account for the considered channelization and service type models.

The general transition probability from $S_{(k,l)} \rightarrow S_{(i+N,j+M)}$, $P_{(i+N,j+M|i,j)}$, is given by [9, eq. (23)] where it should hold, as a difference from [9], $-i \le N \le M_p - i$ along with $-j \le M \le M_s - j$ for the FCS, and $-j \le M \le M_{s,max} - j$ for the ACS. Functions $a^P_{(i,j,k,l)}$, $d^P_{(i,j,k,l)}$, $a^S_{(i,j,k,l)}$ and $d^S_{(i,j,k,l)}$ in [9, eq. (23)] account for assignment and de-assignment probabilities of primary and secondary users respectively.

In state $S_{(i,j)}$, the probability of having k PUs to assign when also l PU de-assignments occur in I_n, $a^P_{(i,j,k,l)}$, is given by [9, eq. (16)], where variable C therein should be replaced by M_p.

In state $S_{(i,j)}$, the probability of de-assigning k PUs in I_n, $d^P_{(i,j,k)}$, is given by [9, eq. (17)].

Remark In the remainder, SU channelization is simply referred to as $M_s(i,j)$, noting that this value should be conveniently replaced according to channelization schemes FCS and ACS. Specifically, for the assignment process of a SU with ACS we have $M_s(i,j) = M_{s,max}$, indicating that the assignment of a SU in this case depends on the maximum channelization value. Similarly, secondary service rate will be referred to as $\mu_s(i,j)$, where it should be also particularized when referring to TBS and VBS.

In state $S_{(i,j)}$, the probability of having k SUs to assign when also l SU de-assignments occur in I_n, $a^S_{(i,j,k,l)}$, follows a similar structure to [9, eq. (18)], and is given by

$$a^S_{(i,j,k,l)} = \begin{cases} \sum_{m=0}^{\lfloor \psi_{(i,j,k,l)} \rfloor} \bar{a}^S_{(m,j,k,l)} \cdot b_{(m,i)} & \text{if } k > 0 \\ \sum_{m=0}^{\xi_{(i,j,l)}} \bar{a}^S_{(m,j,0,l)} \cdot b_{(m,i)} + \sum_{m=\xi_{(i,j,l)}+1}^{M_p} b_{(m,i)} & \text{if } k = 0 \end{cases}, \tag{10}$$

with

$$\psi_{(i,j,k,l)} = [M_s(i,j) - k - j + l] \cdot [M_p/M_s(i,j)], \tag{11}$$

$$\xi_{(i,j,l)} = \lfloor [M_s(i,j) - 1 - j + l] \cdot [M_p/M_s(i,j)] \rfloor \tag{12}$$

and where, similar to [9, eq. (19)],

$$\bar{a}^S_{(m,j,k,l)} = \begin{cases} P^{SA}_k & \text{if } m < \psi_{(i,j,k,l)} \\ 1 - \sum_{r=0}^{k-1} P^{SA}_r & \text{if } m = \psi_{(i,j,k,l)} \end{cases} \tag{13}$$

is the SU assignment probability conditioned to the sensing of m PUs.

Expression (11) gives the maximum number of sensed PUs ensuring no spectrum collision, whereas expression (12) gives the maximum number of sensed PUs yielding one single free detected channel. In both (11) and (12) for the FCS we will consider $M_s(i,j) = M_s$, whereas for the ACS $M_s(i,j) = M_{s,max}$.

Finally, the probability of de-assigning k SUs in state $S_{(i,j)}$ during I_n, $d^S_{(i,j,k)}$, is given by [9, eq. (20)]. Function $d^S_{(i,j,k)}$ accounts for the de-assignment of SUs due to sensing [see component function $d^{S,S}_{(i,j,k,l)}$ therein] and the de-assignment of SUs due to service completion [see component function $d^{S,SC}_{(i,j,k)}$ therein]. Whereas $d^{S,SC}_{(i,j,k)}$ is given by [9, eq. (22)], the definition of $d^{S,S}_{(i,j,k,l)}$ for the case of $M_p \neq M_s$ will be described hereafter since it constitutes a significant model contribution with respect to [9].

Accordingly, in state $S_{(i,j)}$, the probability of de-assigning k SUs due to sensing when l SUs are de-assigned due to service completion, $d^{S,S}_{(i,j,k,l)}$, is given, for $0 < k \le j - l$, by

$$d^{S,S}_{(i,j,k,l)} = \begin{cases} b_{(\chi_{(i,j,k,l)},i)} & \text{if } \chi_{(i,j,k,l)} \in \mathbb{Z} \\ 0 & \text{if } \chi_{(i,j,k,l)} \in \mathbb{R} \end{cases}, \tag{14}$$

with $\chi_{(i,j,k,l)} = [M_s(i,j) + k - j + l] \cdot [M_p/M_s(i,j)]$ the number of sensed PUs in $S_{(i,j)}$ leading to the de-assignment of k PUs when l SUs are de-assigned due to service completion. According to (14), it can be shown that rational number of sensed PUs values, i.e. $\chi_{(i,j,k,l)} \in \mathbb{R}$, lead to infeasible de-assignments which are therefore disregarded in the model. For $k = 0$ we have

$$d^{S,S}_{(i,j,0,l)} = 1 - \sum_{r=1}^{j-l} d^{S,S}_{(i,j,r,l)}. \tag{15}$$

G. Steady State Distribution

As in [9], steady state probabilities $P_{(i,j)}$ are obtained using numerical methods [15]. Moreover, the steady state probabilities of the detected states (i.e. including possible sensing errors), $P'_{(i,j)}$, are computed using [9, eq. (24)], where channelization value C therein should be replaced by M_p.

IV. Metrics and Performance Evaluation

A. Performance Metrics

The definition of relevant performance metrics is described in this section. Blocking probability and average throughput definitions in [9, §4.2] and [9, §4.5] respectively are also useful in our analysis.

1) Offered traffic load and expected service times: Whereas for the TBS one can define the offered traffic load as an input parameter, i.e. $T_p = \lambda_p/\mu_p$ and $T_s = \lambda_s/\mu_s$ for PUs and SUs respectively, the offered SU traffic load for the VBS case is affected by the state-dependent service rate $\mu_s = \mu_s(i,j)$. Hence the offered secondary traffic has to be computed a posteriori. The average residence time (or average transfer

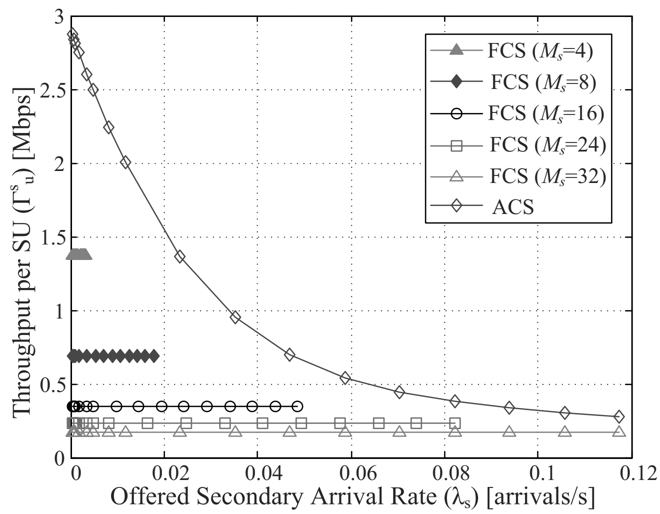

Fig. 2. Average throughput-per-SU comparison between the FCS with $M_s = \{4, 8, 16, 24, 32\}$ and the ACS for the case of TBS. The offered PU arrival rate is $\lambda_p = 0.02$ arrivals/s.

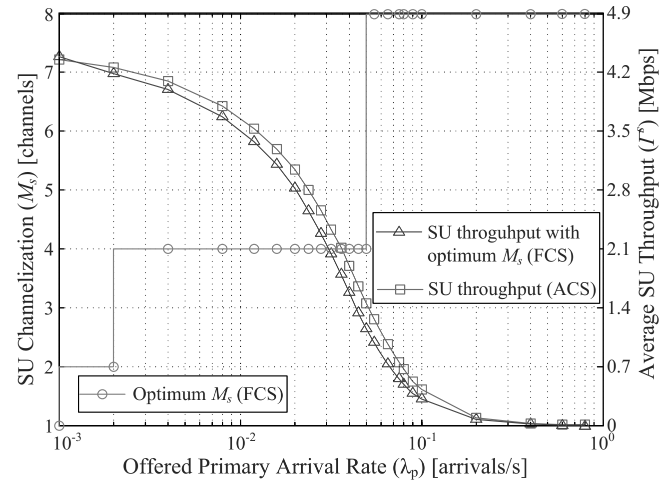

Fig. 3. Optimum SU channelization and corresponding SU throughput for FCS along with the SU throughput for the ACS. The offered SU arrival rate is $\lambda_s = 0.05$ arrivals/s.

delay) for a SU $E[t_s]$ can be computed as

$$E[t_s]=\left(\sum_{S_{(i,j)}\in\mathcal{S},j>0}\frac{1}{\mu_s(i,j)}\cdot P_{(i,j)}\right)\Bigg/\left(\sum_{S_{(i,j)}\in\mathcal{S},j>0}P_{(i,j)}\right), \tag{16}$$

where the denominator reflects the conditioning over $j > 0$. Consequently, using Little's law, the offered secondary load for the VBS yields $T_s = \lambda_s \cdot E[t_s]$. Note that for TBS we would have $E[t_s]=1/\mu_s$.

2) Throughput-per-secondary user: Throughput-per-SU in state $S_{(i,j)}$ is given by $\Gamma^s_u(i,j)=\Gamma^s_{(i,j)}/j$, for $j>0$ and $\Gamma^s_{(i,j)}$ defined in [9, eq. (39)]. Then, the average throughput-per-SU yields

$$\Gamma^s_u=\left(\sum_{S_{(i,j)}\in\mathcal{S},j>0}\Gamma^s_{(i,j)}\cdot P_{(i,j)}\right)\Bigg/\left(\sum_{S_{(i,j)}\in\mathcal{S},j>0}P_{(i,j)}\right). \tag{17}$$

B. Performance Evaluation

Numerical results evaluating the proposed channelization mechanisms and service types are given next. Primary channelization is fixed to M_p=8 and PUs always request TBSs. Secondary channelization set is $\mathcal{M}_s=\{1, 2, 4, 8, 16, 24, 32\}$, i.e. with $M_{s,max} = 32$. Total bandwidth is $W_T = 1.6$MHz and the mean data size for VBS is, unless otherwise stated, $E[L]$=2Mbytes. The average service time of a TBS is 120s.

1) TBS with FCS vs. ACS: In terms of throughput-per-SU [Γ^s_u, defined in (17)], Fig. 2 shows the better performance of the ACS with respect to the FCS (plotted in the range such that blocking probabilities are at most 5%). In particular, when the offered rate is low, the ACS is able to adjust the channelization such that spectrum is not underutilized. When the offered arrival rate is increased, the performance of the ACS converges towards the FCS case with $M_s = 32$ since the maximum channelization for the ACS is also 32 channels. As expected, the FCS exhibits constant throughput-per-SUs values, insensitive to the offered SU arrival rate.

Fig. 3 plots, as a function of the offered PU arrival rate, the (optimum) SU channelization (M_s) that maximizes the average SU throughput, as defined in [9, eq. (43)]. In addition, the corresponding average SU throughput is also plotted and compared to the case of the ACS. Results indicate the need to increase the channelization value as the number of PUs accessing the spectrum increases. In addition, this increase in M_s must be carefully controlled in order to avoid excessive channelization which, in turn, would imply spectrum underutilization and, thus, reduced throughput. The ACS is able to provide an improved performance to that of the FCS with optimum channelization due to its inherent flexibility in allocating spectrum resources. It must be noted that blocking limitations (i.e. ensuring minimum blocking) do not apply in this particular case. In this sense, the ACS achieves improved throughput performance along with reduced blocking probabilities as compared to the FCS.

2) VBS with FCS vs. ACS: In Fig. 4, the blocking probability of SUs is plotted against the average data bulk size that a VBS should deliver. According to (9) and (16), an increase in the average data length $E[L]$ is equivalent to increase in the offered secondary load, $T_s = \lambda_s \cdot E[t_s]$, since the average service time $E[t_s]$ increases with the data length. Then, as shown in Fig. 4, the ACS reflects an improved performance with respect to the FCS especially when the data bulk sizes are large.

3) Sensing error impact in FCS/ACS for TBS: Fig. 5 shows the aggregate throughput (defined in [9, §4.5]) for the ACS and the FCS for TBS when perfect and erroneous sensing applies. As expected, the performance of the erroneous case is worse than the perfect sensing case for both the ACS and FCS. Noteworthy for the FCS the degradation increases with λ_s whereas for the ACS the degradation is fairly constant throughout the whole span of λ_s values. The false-alarm mainly affects the FCS by reducing the number of admitted SUs in the system given it detects PUs which are actually not occupying resources. This effect will be noticeable when λ_s increases since spectrum resources become scarce. As for the ACS, its operation is based on dynamically adjusting the

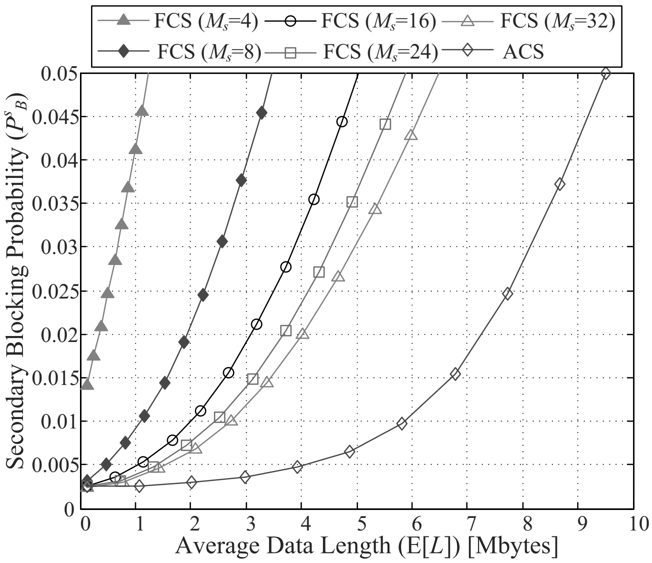

Fig. 4. Secondary blocking probability for the FCS and the ACS against file size when VBS. The offered PU arrival rate is $\lambda_p = 0.02$ arrivals/s and the offered SU arrival rate is $\lambda_s = 0.05$ arrivals/s.

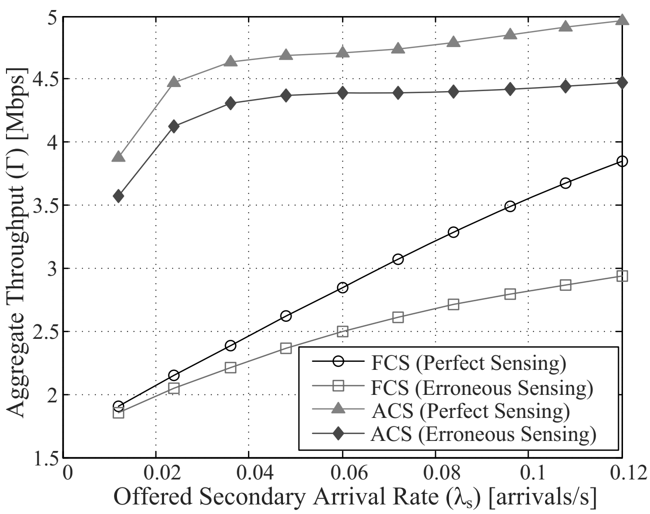

Fig. 5. Aggregate throughput comparison between ACS and FCS (with $M_s = 32$) for TBS when perfect sensing and erroneous sensing applies. For the error case, miss-detection probability is $\delta = 0.01$ and false-alarm probability is $\varepsilon = 0.0974$ (see [9] for further details on these values). In addition, the sensing time is $T = 0.001$s/channel. The offered PU arrival rate is $\lambda_p = 0.02$ arrivals/s.

channelization based on the detection of PUs. This may affect the performance of the ACS even if λ_s is low, thus explaining the similar degradation in the whole range of λ_s values.

V. Conclusions

In this letter we have addressed the impact of channelization schemes in a primary-secondary opportunistic spectrum sharing system. Two channelization alternatives, namely FCS and ACS, have been proposed, modeled and evaluated in a Markovian framework. In addition, the service characterization of SUs has also been addressed considering two different types of services: a time-based service (TBS) and a volume-based service (VBS). Both service characterizations have been evaluated in the context of the abovementioned framework with the FCS and ACS. Numerical results indicate the suitability of the ACS with respect to the FCS given its ability to provide increased bit-rates at lower blocking probability for both time-based and volume-based services. In addition, ACS has proven to be more resilient to sensing errors. Despite this, it should be noted that the operation of the ACS involves a higher complexity in terms of signaling which is necessary to update and inform all SUs about the channelization value M_s. Future work should be devoted to explore the trade-off between the obtained gains with respect to the FCS and this complexity increase.

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