Cognitive Relaying and Opportunistic Spectrum Sensing in Unlicensed Multiple Access Channels

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***Abstract*—In this paper, a cognitive multiple access channel with one primary node and M secondary nodes is considered, and the impact of the following techniques on the stability region of the system is investigated: (*i*) relaying by the secondary nodes of the primary traffic (cognitive relaying); (*ii*) opportunistic spectrum sensing at the secondary nodes. Specifically, inner bounds on the stability region of the system for the case of $M = 2$ secondary nodes are derived by assuming cognitive relaying and both simultaneous and opportunistic spectrum sensing at the secondary nodes. The analysis is carried out by defining convenient systems which statistically dominate the original ones (dominant systems). Numerical results provide insight into the performance advantages of the different strategies in terms of stability region.**

I. Introduction

The cognitive radio principle prescribes the coexistence of licensed (or primary) and unlicensed (or secondary) users in the same spectral resource. In this framework, a possible synchronous TDMA-based implementation is the following: primary nodes are licensed to transmit whenever they have packets, while secondary users continuously sense the channel and transmit only in the time-slots in which no primary activity is detected. Within this choice, interference possibly arises in two cases: (*i*) during time-slots occupied by the primary activity, the secondary nodes, due to unavoidable impairments affecting their sensing phase, possibly access the channel, thus causing interference to the licensed user; (*ii*) during time-slots left idle by the primary, if secondary access to the channel is based on a simultaneous sensing of spectral resource, unlicensed users might interfere with each other.

In this context, the main technological challenge is the design of protocols able to maximize the performance of the secondary nodes (e.g., in terms of stable throughput), while still guaranteeing given QoS constraints on the activity of the primary users [1]-[4]. In [3] [4], a decision-theoretic framework is adopted to find the best sensing and access strategy for secondary nodes, under simplified assumptions about the dynamic behavior of the primary traffic (which is assumed to be stationary and independent of secondary decisions). In contrast, in [5] and [6], the interaction between primary and secondary dynamic behavior is accounted for by a queueing theoretic analysis, and simple static "sense-before-talk" transmission strategies are considered. In this paper, we follow the framework of [5] [6] by focusing on a multiple access cognitive network as in [6], where M secondary nodes coexist with one primary user to transmit to the same access point (see fig. 1). While [6] considered only the basic "sense-before-talk" mechanism at the secondary nodes, here we are interested in assessing the benefits of two more advanced technologies, namely cognitive relaying [5] and opportunistic spectrum sensing [7]. In the remaining part of this introduction, we briefly recall these two techniques. In the paper, performance advantages (in terms of stability region) will be investigated for both their exclusive and joint deployment in the system of fig. 1.

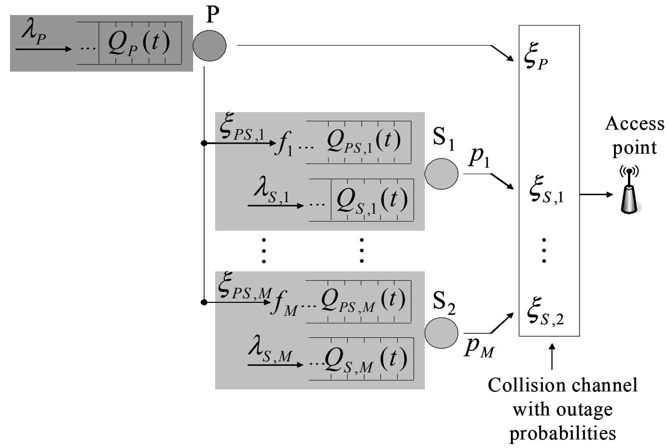

Fig. 1. Cognitive multiple access system: one primary node and M secondary nodes with relaying capability coexist in the same spectal resource.

A. Cognitive relaying

In [5], cognitive relaying is defined as the capability of secondary users to relay the traffic coming from a primary transmitter towards the intended destination. The rationale of this technology is that helping the primary increase its throughput entails (for a fixed demand of rate by the primary) a diminished channel occupancy of the primary, which in turns leads to more transmission opportunities for the secondary [5]. Clearly, the increased number of available slots for the secondary nodes has to be shared between the transmission of own packets and relayed primary packets. It should be noticed that this approach to relaying cognitive radio contrasts with [8] [9], where cooperation was used to avoid simultaneous secondary and primary transmissions, under restrictive

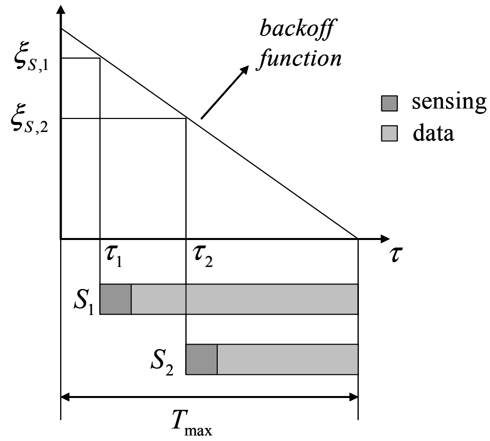

Fig. 2. Schematic representation of the cognitive opportunistic spectrum sensing technique: each secondary node S_i ($i = 1, 2$), based on the quality $\xi_{S,i}$ of its respective channel towards the access point, decides the instant τ_i of sensing the radio bandwidth (within the allowed interval $T_{\max}$) according to a backoff function [4].

assumptions on channel state information availability [10]. The benefits arising from the cognitive relaying mechanism on the stability region of the system will be shown in Sec. V.

B. Cognitive opportunistic spectrum sensing

In order to limit secondary mutual interference in idle time-slots (point (*ii*) above), a promising solution is represented by *opportunistic* spectrum sensing, which is here based on the opportunistic carrier sensing method proposed in [7]. The main idea is that each secondary node senses the channel at different time instants as determined on the basis of a common backoff function deterministically known at all the users and, if no activity is detected, it accesses the channel. Specifically, the backoff function is a mapping between a measure of the channel quality into the instant when the secondary is allowed to sense the surrounding radio environment: the worse the channel, the later the secondary node performs sensing (see fig. 2). Thanks to this mechanism, in an idealistic scenario where no missed detections occur and there is no propagation delay between unlicensed users, a secondary node will transmit, with its chosen backoff delay, if and only if no other secondary user with better channel quality transmits before its detection is ended. The effect of this technique on the performance of the system in terms of stability region will be studied in Sec. IV accounting for errors in the detection phase.

II. System model

We consider the cognitive scenario in fig. 1, where a primary licensed node P and M secondary nodes S_i ($i \in \mathcal{M} = \{1, 2, ..., M\}$) with relaying capability with respect to the primary traffic transmit in the same spectral resource to a common receiver (e.g., access point). We refer to this system as $\Omega^{(M)}$ in the following.

As for the physical layer, we consider a modified collision model, where a packet is correctly detected by the destination if and only if no concurrent transmission takes place and there is no decoding error. A decoding error occurs independently from anything else with a probability $1-\xi_i$, with the subscript i identifying the link (specifically, i reads "P" for the link from the primary node to the access point, "S, j" for the link from the jth secondary node to the access point, and "PS, j" for the link from the primary node to the jth secondary node). When a packet is not correctly received by destination, it needs to be retransmitted. The arrival processes of the exogenous packets at each node are independent and i.i.d. Bernoulli processes with mean λ_P [packets/slot] for the primary user and $\lambda_{S,i}$ [packets/slot] for the ith secondary node ($i \in \mathcal{M}$). Time is slotted and all the packets have the same length, equal to one time slot (the average arrival rates, thus, correspond to the probabilities of an arrival at a given node in a given time slot).

Let $Q_P(t)$ be the stochastic process referring to the number of exogenous packets stored in the queue of the primary node and, similarly, let $Q_{S,i}(t)$ and $Q_{PS,i}(t)$ refer to the number of packets stored by secondary node S_i in the queue devoted to the exogenous traffic and the primary relayed traffic, respectively. In the presence of secondary relaying, a primary packet which is not correctly decoded at the receiver might be correctly decoded at a secondary node S_i (under the assumption that it has succeeded in the detection) with probability $\xi_{PS,i}$, and, then, accepted in the relaying queue $Q_{PS,i}(t)$ with a *packet acceptance probability* f_i. Notice that, when $f_i = 0$ for each $i \in \mathcal{M}$, the relaying capability of the cognitive radio system is lost. Since multiple secondary nodes might decide to accept a primary packet according to the mechanism described above, here we assume that the packet is stored only in the relaying queue $Q_{PS,i}$ of the secondary node with the best channel condition $\xi_{S,i}$. This requires some minor overhead which is not further accounted for in the analysis.

The primary node P attempts transmission whenever it has packets in its queue, while any secondary node S_i ($i \in \mathcal{M}$), at each time slot, senses the channel and, if no activity is detected, transmits a packet with probability p_i (random access) giving priority to the relaying queue $Q_{PS,i}$ with respect to queue $Q_{S,i}$. In other words, the secondary node S_i, provided that an idle slot has been sensed, transmits a packet from queue $Q_{S,i}$ if and only if the relaying queue $Q_{PS,i}$ is empty. When no opportunistic spectrum sensing is performed, all the secondary nodes perform sensing simultaneously, while the opposite is true for opportunistic spectrum sensing (see fig. 2). Details on sensing will be provided in Sec. III and in Sec. IV for the case of simultaneous and opportunistic channel sensing, respectively.

III. Stability analysis for simultaneous spectrum sensing

In this section, we consider the cognitive multiple access channel of fig. 1 with $M = 2$ unlicensed nodes (possibly acting as cognitive relays) for the case of simultaneous spectrum sensing. Due to unavoidable errors, any secondary transmitter S_i can correctly detect the activity of the primary user with a probability $P_{d,i}$ (probability of detection), while it can detect primary activity even in an idle slot and, consequently, miss an opportunity for transmission with a probability $P_{fa,i}$ (probability of false alarm). From the stated assumptions, in a given *idle* time-slot, any secondary node S_i, if its queues $Q_{PS,i}(t)$ and $Q_{S,i}(t)$ are not simultaneously empty, attempts the transmission of a packet with probability

$$\theta_i = p_i(1 - P_{fa,i}). \tag{1}$$

Finally, the outcome of the detection at any secondary node is considered independent of the other secondary users.

Here, we derive an inner bound on the stability region $\mathcal{S}^{(2)}$ of the average arrival rates $\lambda_{S,i}$ to the secondary nodes for which the whole system is stable, i.e., all the queues are stable. As in, e.g., [11], a queue $Q(t)$ is said to be stable if and only if its probability of being empty does not vanish as time progresses: $\lim_{t\to+\infty} \Pr[Q(t) = 0] > 0$. When studying stability of interacting queues, a key concept is that of dominant systems, which, in general, allows to obtain sufficient conditions for stability: by construction, if a dominant system is stable, then the original system is [11]. Applying this idea to our system as in [6], here we introduce the following class of dominant systems:

$$\bar{\boldsymbol{\Omega}}^{(M)} = \left\{ \bar{\Omega}_{\mathcal{V}}^{(M)} \right\}_{\mathcal{V}\subseteq\mathcal{M}}, \tag{2}$$

where $\bar{\Omega}_{\mathcal{V}}^{(M)}$ is any system which differs from the original system $\Omega^{(M)}$ for two facts: (*i*) in any time-slot occupied by the primary transmission, every secondary user $\{\mathrm{S}_i\}_{i\in\mathcal{M}}$, if failing the detection, transmits a (possibly dummy) packet from queue $Q_{S,i}$ with probability p_i even if queue $Q_{S,i}$ is empty; (*ii*) in any time slot left idle by the primary user, each secondary node belonging to the set $\mathcal{V}$ continues to transmit dummy packets from its queue $Q_{S,i}$ with probability θ_i defined in (1) even if its queue $Q_{S,i}$ is empty. Since transmission of dummy packets does not decrease the queue sizes but can still cause collisions, any system belonging to the class $\bar{\boldsymbol{\Omega}}^{(M)}$ is a dominant system with respect to the original system $\Omega^{(M)}$: any average arrival rates set $\{\lambda_{S,i}\}_{i\in\mathcal{M}}$ which can be supported in any system $\bar{\Omega}_{\mathcal{V}}^{(M)}$ can also be supported in $\Omega^{(M)}$. Finally, we remark that in the following analysis we assume that $\xi_{S,1} > \xi_{S,2}$, which implies that a primary packet which is accepted by both secondary nodes is stored only in S_1.

A. Inner bound on $\mathcal{S}^{(2)}$ with cognitive relaying and simultaneous spectrum sensing

The goal of this section is to find an inner bound on the (stability) region $\mathcal{S}^{(2)}$ of the average arrival rates $\{\lambda_{S,1}, \lambda_{S,2}\}$ at the secondary nodes S_1, S_2 for which at least one combination of the transmission probabilities $\mathbf{p} = [p_{1,}, p_2]$ and of the packet acceptance probabilities $\mathbf{f} = [f_1, f_2]$ exist that guarantees stability of the secondary queues $\{Q_{S,1}, Q_{S,2}\}$, under the requirement of stability for all the queues and given system parameters $[\lambda_P, \{P_{d,i}\}_{i\in\mathcal{M}}, \{P_{fa,i}\}_{i\in\mathcal{M}}, \{\xi_{PS,i}\}_{i\in\mathcal{M}}, \{\xi_{S,i}\}_{i\in\mathcal{M}}, \xi_P]$. According to the definition above, the stability region $\mathcal{S}^{(2)}$ can be expressed as:

$$\mathcal{S}^{(2)} = \left\{ \bigcup_{\mathbf{p},\mathbf{f}} \tilde{\mathcal{S}}^{(2)}(\mathbf{p},\mathbf{f}) \mid p_i, f_i \in [0,1], \text{with } i = 1,2 \right\}, \tag{3}$$

where $\tilde{\mathcal{S}}^{(2)}(\mathbf{p},\mathbf{f})$ is the stability region of the average arrival rates $\lambda_{S,1}$, $\lambda_{S,2}$ at the secondary nodes for given transmission probabilities $\mathbf{p}$ and packet acceptance probabilities $\mathbf{f}$.

An inner bound on the stability region $\mathcal{S}^{(2)}$ is derived in the following by considering the class of dominant systems $\bar{\boldsymbol{\Omega}}^{(2)}$. In particular, we focus on systems $\bar{\Omega}_1^{(2)}$ and $\bar{\Omega}_2^{(2)}$ according to (2), with $\mathcal{V} = \{1\}$ and $\mathcal{V} = \{2\}$, respectively. Since, as discussed in [12], in both dominant systems the arrival and the departure rates of all the queues are stationary processes, Loynes' theorem can be employed to draw conclusions on the stability of each queue [13]. Furthermore, stationarity of the involved processes also implies that, in a given dominant system $\bar{\Omega}_j^{(2)}$, the probability that queue $Q_k(t)$ is empty is given via Little's theorem by:

$$\mathrm{P}[Q_k(t) = 0] = \eta_k^j = (1 - \lambda_k^j/\mu_k^j), \tag{4}$$

being λ_k^j and μ_k^j the average arrival and departure rate, respectively. As a consequence, stability of the primary queue in both dominant systems is guaranteed if (sufficient condition)

$$\lambda_P < \mu_P, \tag{5}$$

where the average departure rate μ_P is easily shown to read by enumerating the events where a primary packet is dropped by queue $Q_P(t)$:

$$\begin{aligned}\mu_P \;\; = \;\; & P_{d,1}P_{d,2}[\xi_P + \bar{\xi}_P(\xi_{PS,1}f_1 + \\ & \bar{\xi}_{PS,1}\xi_{PS,2}f_2 + \xi_{PS,1}\bar{f}_1\xi_{PS,2}f_2)] + \\ & \bar{P}_{d1}\bar{P}_{d2}\bar{p}_1\bar{p}_2\xi_P + \bar{P}_{d,1}P_{d,2}\bar{p}_1(\xi_P + \\ & \bar{\xi}_P\xi_{PS,2}f_2) + \bar{P}_{d2}P_{d1}\bar{p}_2(\xi_P + \bar{\xi}_P\xi_{PS,1}f_1),\end{aligned} \tag{6}$$

with $\bar{x} = 1 - x$. Let us now focus on dominant system $\bar{\Omega}_1^{(2)}$ and assume that (5) holds true. Using the same arguments as in [11], from Loynes' theorem, stability of the secondary queue $Q_{PS,2}(t)$ is guaranteed if:

$$\lambda_{PS,2}^1 < \mu_{PS,2}^1, \tag{7}$$

where the superscript 1 is a mnemonic for system $\bar{\Omega}_1^{(2)}$, $\lambda_{PS,2}^1$ is the average arrival rate at the relaying queue $Q_{PS,2}(t)$, given by

$$\lambda_{PS,2}^1 = \bar{\eta}_P\bar{\xi}_P P_{d,2}\xi_{PS,2}f_2(P_{d,1}(\xi_{PS,1}\bar{f}_1 + \bar{\xi}_{PS,1}) + \bar{P}_{d,1}\bar{p}_1), \tag{8}$$

where, according to assumption (*i*) made in Sec. III for dominant systems $\bar{\boldsymbol{\Omega}}^{(2)}$, $\eta_P = \eta_P^1 = \eta_P^2 = 1 - \lambda_P/\mu_P$, while $\mu_{PS,2}^1$ is the average departure rate from queue $Q_{PS,2}(t)$, which is given by:

$$\mu_{PS,2}^1 = \eta_P\theta_2\bar{\theta}_1\xi_{S,2}. \tag{9}$$

In the same way, stability of the secondary queue $Q_{S,2}(t)$ is guaranteed if:

$$\lambda_{S,2} < \mu^1_{S,2}, \tag{10}$$

where:

$$\mu^1_{S,2} = \eta^1_{PS,2}\mu^1_{PS,2}. \tag{11}$$

As for the secondary user S_1, the average arrival rate $\lambda^1_{PS,1}$ at queue $Q_{PS,1}(t)$ reads:

$$\lambda^1_{PS,1} = \bar{\eta}_P\bar{\xi}_P P_{d,1}\xi_{PS,1} f_1(P_{d,2} + \bar{P}_{d,2}\bar{p}_2), \tag{12}$$

while the average departure rate $\mu^1_{PS,1}$ from queue $Q_{PS,1}(t)$ is equal to $\eta_P\theta_1\bar{\theta}_2\xi_{S,1}$ if the secondary user S_2 has at least one non-empty queue (which happens with probability $\Gamma^1_{F,2}$) or equal to $\eta_P\theta_1\xi_{S,1}$ if secondary user S_2 has two empty queues (which happens with probability $\Gamma^1_{E,2}$), so that $\mu^1_{PS,1}$ reads:

$$\mu^1_{PS,1} = \eta_P(\Gamma^1_{F,2}\theta_1\bar{\theta}_2 + \Gamma^1_{E,2}\theta_1)\xi_{S,1}, \tag{13}$$

with $\Gamma_{F,2}$ and $\Gamma_{E,2}$ defined as:

$$\Gamma_{F,2} = \eta^1_{PS,2}\bar{\eta}^1_{S,2} + \bar{\eta}^1_{PS,2}\eta^1_{S,2} + \eta^1_{PS,2}\eta^1_{S,2}, \tag{14}$$

$$\Gamma_{E,2} = \bar{\eta}^1_{PS,2}\bar{\eta}^1_{S,2}. \tag{15}$$

Given this, by Loynes' theorem, stability of the secondary queue $Q_{PS,1}(t)$ is guaranteed if

$$\lambda^1_{PS,1} < \mu^1_{PS,1}, \tag{16}$$

while stability of the secondary queue $Q_{S,1}(t)$ is guaranteed if

$$\lambda_{S,1} < \mu^1_{S,1}, \tag{17}$$

where, as detailed in [12],

$$\mu^1_{S,1} = \eta^1_{PS,1}\mu^1_{PS,1}. \tag{18}$$

To sum up, from consideration of the dominant system $\bar{\Omega}^{(2)}_1$, the conditions (7), (10), (16), (17) provide an inner bound on the stability region $\tilde{\mathcal{S}}^{(2)}(\mathbf{p}, \mathbf{f})$. Moreover, following the same approach for the dominant system $\bar{\Omega}^{(2)}_2$, we obtain further sufficient conditions for stability:

$$\begin{cases} \lambda^2_{PS,1} < \mu^2_{PS,1} = \eta_P\theta_1\bar{\theta}_2\xi_{S,1} \\ \lambda_{S,1} < \mu^2_{S,1} = \eta^2_{PS,1}\mu^2_{PS,1} \\ \lambda^2_{PS,2} < \mu^2_{PS,2} = \eta_P(\Gamma^2_{F,1}\theta_2\bar{\theta}_1 + \Gamma^2_{E,1}\theta_2)\xi_{S,2} \\ \lambda_{S,2} < \mu^2_{S,2} = \eta^2_{PS,2}\mu^2_{PS,2} \end{cases} \tag{19}$$

where $\lambda^2_{PS,1}$ and $\lambda^2_{PS,2}$ are equal to (12) and (8), respectively, and $\Gamma^2_{F,1}$ and $\Gamma^2_{E,1}$ are obtained from (14) and (15), respectively, by substituting the subscript 2 with 1 and the superscript 1 with 2.

In conclusion, equations (5), (7), (10), (16), (17) and (19), considered at the same time, define an inner bound on the stability region $\tilde{\mathcal{S}}^{(2)}(\mathbf{p}, \mathbf{f})$. Then, an inner bound on the stability region $\mathcal{S}^{(2)}$ is easily obtained from (3). Analytically, each point on the boundary of the stability region $\mathcal{S}^{(2)}$ can be obtained by solving an optimization problem: fixed $\lambda_{S,1} = \bar{\lambda}_{S,1}$, maximize $\lambda_{S,2}$ (or viceversa) with respect to the transmission probabilities $\mathbf{p}$ and the acceptance probabilities $\mathbf{f}$ under the constraints on the stability of all the queues in the system.

IV. Stability analysis for opportunistic spectrum sensing

In this section, the impact of opportunistic spectrum sensing at the secondary nodes is investigated as a means of enlarging the stability region of the system. As far as the system model is concerned, the main difference with respect to the simultaneous sensing case treated in the previous section is that the probability that a given secondary node S_i transmits in a slot left idle by the primary - provided that it has at least one packet in its queue - depends on the behavior of the other secondary nodes. In particular, this probability reads:

$$\theta^{(0)}_i = \theta_i \tag{20}$$

conditioned on the event that no other secondary user, accordingly to the selected backoff function, has attempted transmission before S_i, while it reads:

$$\theta^{(\mathcal{K})}_i = (1 - P^{(\mathcal{K})}_{d,i})p_i, \tag{21}$$

otherwise, where $P^{(\mathcal{K})}_{d,i}$ is the probability that the ith secondary user correctly performs the detection given that a set $\mathcal{K} \subseteq \mathcal{M}$ (with $|\mathcal{K}| > 0$) of secondary users have started transmission before it. We remark that, for detectors based on the received signal to noise ratio (such as the energy detector), we generally have that $P^{(\mathcal{K}')}_{d,i} > P^{(\mathcal{K}'')}_{d,i}$ if $|\mathcal{K}'| > |\mathcal{K}''|$, and $P^{(\mathcal{K})}_{d,i}$ depends on the network topology between the secondary user S_i and the nodes belonging to the given set $\mathcal{K}$.

Accordingly, for the case $M = 2$, under the assumption that $\xi_{S,1} > \xi_{S,2}$, which implies that S_1 performs detection before S_2, an inner bound to the stability region is still obtained by equations (5), (7), (10), (16), (17) and (19) by substituting $\mu^1_{PS,1}$ and $\mu^2_{PS,1}$ with:

$$\mu^1_{PS,1} = \eta_P(\Gamma^1_{F,2}\theta_1\bar{\theta}^{(1)}_2 + \Gamma^1_{E,2}\theta_1)\xi_{S,1}, \tag{22}$$

$$\mu^2_{PS,1} = \eta_P\theta_1\bar{\theta}^{(1)}_2\xi_{S,1}, \tag{23}$$

respectively, since, in our model, opportunistic spectrum sensing has the unique effect of making that, in an idle time slot, packets from node S_1 not experience collision if secondary node S_2 either is able to correctly detect the activity of S_1 (which happens with probability $P^{(1)}_{d,2}$), or it misses detection but decides not to transmit (which happens with probability $\bar{P}^{(1)}_{d,2}\bar{p}_2$).

V. Numerical results

In order to get insight into the performance advantages of cognitive relaying, fig. 3 shows the guaranteed percentage gains in terms of the maximum stable average arrival rate $\lambda_{S,2}$ (for fixed $\lambda_{S,1} = 0.15$) with respect to the no relaying strategy (i.e., $f_1 = f_2 = 0$, see also [6]) versus ξ_P for different values of the parameter $\xi_{S,1}$ (other system parameters are selected as $\lambda_P = 0.15$, $\xi_{S,2} = \xi_{S,1} - 0.05$, $\xi_{PS,i} = 0.78$, $P_{d,i} = 0.9$, $P_{fa,i} = 0.05$, for $i = 1, 2$). For very small values of ξ_P (in the range $0 - 0.3$), this gain (not shown) goes to infinity because of the vanishing throughput obtained with no relaying case [6]. For $\xi_P > 0.3$, the relaying policy guarantees large

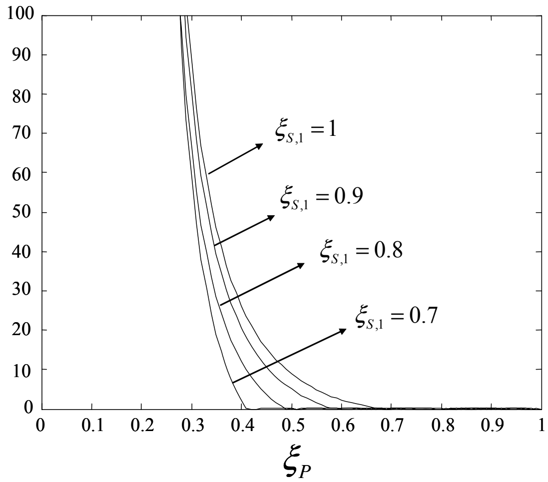

Fig. 3. Percentage gain guaranteed by the cognitive relaying policy in terms of the maximum stable average arrival rate $\lambda_{S,2}$ (for fixed $\lambda_{S,1} = 0.15$) with respect to the no relaying strategy ($f_1 = f_2 = 0$ [6]) versus ξ_P for different values of the parameter $\xi_{S,1}$ (other system parameters are selected as $\lambda_P = 0.15$, $\xi_{S,2} = \xi_{S,1} - 0.05$, $\xi_{PS,i} = 0.78$, $P_{d,i} = 0.9$, $P_{fa,i} = 0.05$, for $i = 1, 2$)

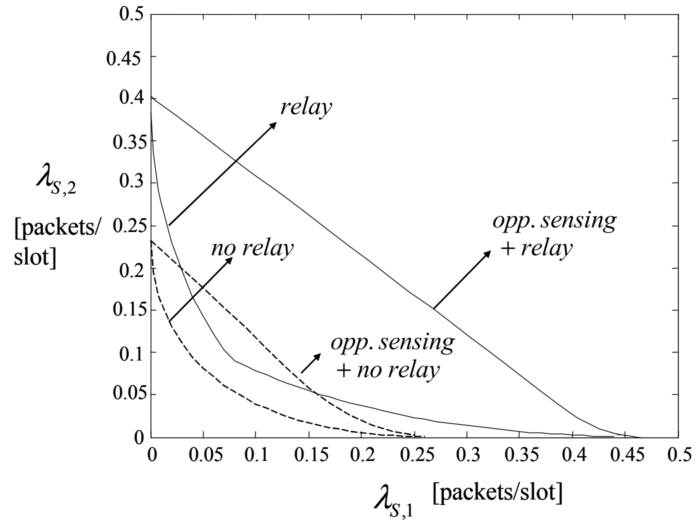

Fig. 4. Comparison of the stability regions $\mathcal{S}^{(2)}$ obtained with no relaying ($f_1 = f_2 = 0$ [6]) and with relaying both with and without secondary opportunistic spectrum sensing. System parameters are selected as: $\lambda_P = 0.25$, $\xi_P = 0.4$, $\xi_{S,1} = 0.9$, $\xi_{S,2} = \xi_{PS,1} = \xi_{PS,2} = 0.8$, $P_{d,i} = 0.9$, $P_{fa,i} = 0.05$ ($i = 1$, 2) and $P^{(1)}_{d,2} = 0.94$.

throughput gains until ξ_P approximately reaches values around $\xi_{S,1} - 0.3$. After this value, cognitive relaying does not provide performance gains with respect to the no relaying policy. An intuitive explanation of this can be found in considering that cognitive relaying is able to outperform no relaying policy only when the relaying path (accounted for by $\xi_{S,i}$, $\xi_{PS,i}$) is better than the direct primary channel (accounted for by ξ_P).

The benefits arising from the use of opportunistic with respect to simultaneous spectrum sensing are illustrated in fig. 4, which shows a comparison of the stability regions $\mathcal{S}^{(2)}$ obtained for the no relaying case ($f_1 = f_2 = 0$) and for the relaying case both with and without secondary opportunistic spectrum sensing. System parameters are selected as: $\lambda_P = 0.25$, $\xi_P = 0.4$, $\xi_{S,1} = 0.9$, $\xi_{S,2} = \xi_{PS,1} = \xi_{PS,2} = 0.8$, $P_{d,i} = 0.9$, $P_{fa,i} = 0.05$ ($i = 1$, 2), and $P^{(1)}_{d,2} = 0.94$. The figure suggests that the opportunistic spectrum sensing mechanism leads to a wider stability region $\mathcal{S}^{(M)}$ both for the relaying and no relaying case. In particular, the quasi-linear shape of the bounds derived for the opportunistic spectrum sensing case provides evidence of a very efficient exploitation of the usable bandwidth. Finally, it can be noticed that, at the secondary node with higher channel quality (in this case S_1), larger stable arrival rates can be achieved with respect to the other one.

VI. Conclusions

In this paper, we have focused on a cognitive multiple access scenario composed of one primary and two secondary nodes. The advantages of allowing the secondary nodes to act as relaying nodes for the primary traffic and of opportunistic spectrum sensing have been investigated in terms of enhancement of the system stability region.

References

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journ. Selected Areas Commun.*, vol. 23, no. 2, pp. 201-220, Feb 2005.

[2] J. O. Neel, “Analysis and Design of Cognitive Radio Networks and Distributed Radio Resource Management Algorithms,” PhD. dissertation, Virginia Polytechnic Institute, September 2006.

[3] L. Lai, H. El Gamal, H. Jiang and H. V. Poor , "Cognitive medium access: exploration, exploitation and competition," [available on-line http://arxiv.org/PS_cache/arxiv/pdf/0710/0710.1385v1.pdf].

[4] Q. Zaho, L. Tong, A. Swami, Y. Chen, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework," *IEEE Journ. Selected Areas Commun.*, vol. 25, no. 3, pp. 589-600, April 2007.

[5] O. Simeone, Y. Bar-Ness and U. Spagnolini, “Stable throughput of cognitive radios with and without relaying capability,” *IEEE Trans. Comm.*, vol. 55, no. 12, pp. 2351- 2360, December 2007.

[6] J. Gambini, O. Simeone, Y. Bar-Ness and U. Spagnolini, “Stability analysis of a cognitive multiple access channel with primary QoS constraints,” in *Proc. IEEE Asilomar Conference on Signals, Systems and Computers 2007.*

[7] Q. Zaho and L. Tong, "Opportunistic Carrier Sensing for Energy-Efficient Information Retrieval in Sensor Networks," *EURASIP Journal on Wireless Comm. and Networking*, no. 2, pp. 231-241, 2005.

[8] N. Devroye, P. Mitran and V. Tarokh, “Limits on communications in a cognitive radio channel,” *IEEE Commun. Magazine*, vol. 44, no. 6, pp. 44-49, June 2006.

[9] A. Jovicic and P. Viswanath, “Cognitive radio: an information-theoretic perspective,” submitted to *IEEE Trans. Inf. Theory*, 2006 [available on-line: http://lanl.arxiv.org/PS cache/cs/pdf/0604/0604107.pdf].

[10] P. Grover and A. Sahai, “On the need for knowledge of the phase in exploiting known primary transmissions,” in *2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2007, DySPAN 2007*, pp. 462-471, April 2007.

[11] R. Rao and A. Ephremides, “On the stability of interacting queues in a multi-access system,” *IEEE Trans. Inform. Theory*, vol. 34, no. 5, pp. 918-930, Sept. 1988.

[12] J. Gambini, O. Simeone, U. Spagnolini, “Stability analysis of cognitive multiple access channels,” in preparation

[13] R: M. Loynes, “The stability of a queue with non-independent inter-arrival and service times,” in *Proc. Cambridge Philos. Soc.*, vol. 58, pp. 497-520, 1962.