COOPERATIVE COGNITIVE RADIOS WITH OPTIMAL PRIMARY DETECTION AND PACKET ACCEPTANCE CONTROL

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ABSTRACT

In this paper, we investigate the stable throughput of a cognitive interference channel (four nodes: a primary transmitter-receiver pair and a secondary transmitter-receiver pair) with random packet arrivals and possible relaying of primary packets by the secondary transmitter. We extend the previous work [1] by considering the optimal design of the secondary transmitter with the following additional degrees of freedom: *a*) optimization of the detector of the primary activity (trade-off between probability of false alarm and probability of missed detection); *b*) a packet acceptance control mechanism that prevents queue overflow due to the traffic relayed on behalf of the primary. Moreover, we investigate the impact of errors in detecting the primary activity on the queuing delays.

1. INTRODUCTION AND BASIC MODEL

Cognitive radio is regarded as a promising means to achieve efficient utilization of the spectral resource in wireless communications. According to the principle of the cognitive radio, a group of unlicensed (or secondary) radio nodes continuously sense the spectral resource employed by a set of licensed (or primary) radio nodes in order to find possibilities for transmission (i.e., idle periods in the activity of primary transmitters). The main requirement is that the activity of secondary nodes should be completely *transparent* to the primary. Centralized and decentralized cooperative protocols employed by the secondary users to improve performance of detection of the primary activity have been proposed in [2] and [3], while a discussion of the fundamental limits of cognitive radio under a geometric model is presented in [4].

1.1. Cognitive interference channel

An important basic block of a cognitive radio network is the cognitive interference channel, where one primary and one secondary single-link connections share the same bandwidth. This scenario has been first studied from an information theoretic standpoint in [5] [6], assuming backlogged terminals and perfect knowledge at the secondary link of the codeword transmitted by the primary. Random packet arrivals, sensing errors at the secondary link and cooperation have then been introduced in the model of a cognitive interference channel in [1], where the stable throughput of the secondary link is evaluated under different assumptions. In this paper, we extend the analysis of [1], whose contribution is now briefly recalled for reference.

The basic assumptions in [1] include stationary packet arrivals at the two (primary and secondary) transmitters, stationary Rayleigh fading channels and slotted transmission. In short, the primary transmitter accesses the channel whenever it has a packet in its queue $Q_P(t)$ at the beginning of the slot t, being oblivious to the presence of a secondary link. On the other hand, the secondary transmitter sends a packet to its destination in a given slot only if it senses an idle channel (and if it has a packet to transmit in its queue $Q_S(t)$). Moreover, the secondary transmitter accepts a primary packet whenever the packet is not correctly received by the intended destination but is instead decoded at the secondary transmitter, which stores it in a separate queue $Q_{PS}(t)$. The problem in [1] is that of maximizing the *stable throughput* of the secondary link under the constraint of *transparency* towards primary users, by optimally choosing *secondary transmission power* P_S and *scheduling probability* ε. The latter is, with reference to fig. 1, the probability that the secondary node transmits a packet from the relaying queue $Q_{PS}(t)$ when it senses an idle slot. The work presented in [1] further assumes that the secondary transmitter possibly fails to detect a primary transmission, thus causing unwanted interference, but is otherwise able to detect an idle slot with zero probability of error (false alarm). Moreover, a problem pointed out in [1] with the proposed solution, is that the secondary queue devoted to the primary traffic $Q_{PS}(t)$ can overflow if the fading channel to the primary receiver is not good enough to support the relayed transmission. Finally, the analysis presented in [1] adopts as a criterion for transparency the stability of the primary queue (that is, secondary transmissions are transparent to the primary link if the queue of the primary transmitter is stable irrespective of the secondary activity), and thus does not take into account constraints on the average delays of the packets, making the protocols presented not suitable for delay-sensitive applications.

Contributions: In this paper, we extend the work in [1] towards the goal of alleviating the problems discussed above. In addition to the secondary transmission power P_S and scheduling probability ε, here we introduce the following degrees of freedom in the optimization problem discussed above: *a*) we model the detector of the primary activity at the secondary node as an energy detector, and, inspired by [7], investigate the *optimal detection threshold* α that leads to the best trade-off on the receiving operating curve between probability of false alarm (which entails lost transmission opportunities for the secondary) and missed de-

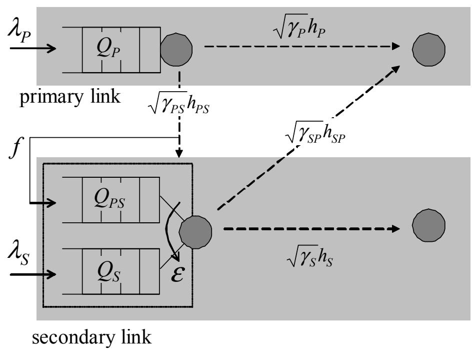

Fig. 1. Cognitive interference channel with relaying capability at the secondary transmitter.

tection (which causes interference on the primary transmission); *b*) in order to alleviate possible problems of congestion at the relaying queue $Q_{PS}(t)$, we study a *packet acceptance scheme* at the secondary node, whereby only a fraction f of the primary packets are forwarded by the secondary (and thus stored in $Q_{PS}(t)$). Finally, we analyze the delay performance of the cognitive interference channel at hand.

2. STABLE THROUGHPUT OF THE COGNITIVE NODE WITH OPTIMIZED PRIMARY DETECTION

We start by considering the problem of optimizing the working point on the operating curve of the detector of the primary activity at the secondary transmitter (optimal detection threshold α). In order to simplify the analysis and isolate different effects, here we concentrate on the baseline case where the secondary transmitter does not relay any packet from the primary (see fig. 1 with queue $Q_{PS}(t)$ being empty at all times and scheduling probability $\varepsilon = 0$).

2.1. System model

Here we illustrate in better detail the basic model of a cognitive interference channel. Both primary and secondary transmitting nodes are equipped with an infinite queue in which incoming packets are stored. All packets have the same number of bits, and their transmission time coincides with a time slot, which we consider as our reference time unit. The arrivals of packets at each transmitting station are independent and stationary processes, with λ_P (packets/ slot) being the mean arrival rate at the primary queue and λ_S (packets/ slot) the mean arrival rate at the secondary queue. As for the signalling protocols, we consider that each receiving node sends the respective transmitting node an ACK message in case of a correct reception or a NACK message in case of an erroneous reception. A packet reception error requires *retransmission*. Notice that the overhead introduced in the system by the transmission of ACK-NACK messages is considered negligible, and therefore not accounted for in this paper.

Independent Rayleigh block-fading channels are assumed between every pair of nodes. In particular, the complex channel gains on the ith link (where subscript i identifies transmitter-receiver pairs as illustrated in fig. 1) at the tth slot read $\sqrt{\gamma_i}h_i(t)$ where $h_i(t)$ is a zero-mean unit-variance stationary process and γ_i is the average (time-invariant) channel power gain. Moreover, the primary transmitter employs unit power ($P_P = 1$), while the secondary transmits with power $P_S \leq 1$. Packet transmission is considered successful if the instantaneous signal-to-noise ratio is above given thresholds β_P for the primary link and β_S for the secondary. Notice that in case of missed detection of primary activity, the secondary interferes with the primary transmission, and in this case primary transmission is successful if the signal-to-noise-plus-interference ratio is above the threshold β_P.

2.2. The energy detector

According to the basic principle of cognitive radio, at the beginning of each slot, the secondary transmitter senses the channel in order to find whether it is occupied by the primary or not. In this paper, differently from [1], we explicitly model the detection (sensing) process by using an energy detector [8]. More precisely, at the beginning of each slot, the secondary node measures m samples (at symbol rate) of the received signal in order to detect whether the primary is active (hypothesis $\mathcal{H}_1$) or idle (hypothesis $\mathcal{H}_0$). The signal received by the secondary at the kth sample of the tth time slot reads (with $k = 1, 2, ..., m$):

$$y_S(k,t) = \begin{cases} n(k,t) & \text{if } \mathcal{H}_0 \\ \sqrt{\gamma_{PS}} \cdot h_{PS}(t)s(k,t) + n(k,t) & \text{if } \mathcal{H}_1 \end{cases}, \quad (1)$$

where $s(k,t)$ is the signal transmitted by the primary transmitter, $n(k,t)$ is additive white Gaussian noise. The output of the energy detector, $U^{(m)}(t) = \sum_{k=1}^{m} |y_S(k,t)|^2$, is used by the secondary transmitter as a decision statistic to be compared with a threshold α. This implies that the secondary succeeds in detecting the primary activity with probability of detection $P_d(\alpha) = P[U^{(m)}(t) > \alpha|\mathcal{H}_1]$ and it fails to detect an idle slot with probability of false alarm $P_{fa}(\alpha) = P[U^{(m)}(t) > \alpha|\mathcal{H}_0] = \Gamma(m, \frac{\alpha}{2})/\Gamma(m)$, where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are complete and incomplete gamma function respectively [9]. Assuming that the channel $h_{PS}(t)$ is known at the secondary[1], the probability of detection $P_d(\alpha)$, averaged over the Rayleigh fading distribution, can be calculated as shown in [9][2]. In the following, we investigate the detection threshold α that results in the optimum trade-off between limiting the interference at the primary (probability of missed detection) and exploiting transmission opportunities (probability of false alarm) towards the goal of maximizing the stable throughput at the secondary.

2.3. Problem formulation and system analysis

The primary transmitter in fig. 1 selects its arrival rate λ_P within its own stability region, being oblivious to the presence of the secondary. On the contrary, the secondary transmitter adapts both its

[1] This is resonable if we assume that the primary transmitter periodically sends a training sequence, known also at the secondary node, to its intended destination.

[2] In particular, using our notation, we have

$$\begin{aligned} P_d(\alpha) &= e^{-\frac{\alpha}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\alpha}{2}\right)^k + \left(\frac{1+\gamma_{PS}}{\gamma_{PS}}\right)^{m-1} \\ &\quad \times e^{-\frac{\alpha}{2(1+\gamma_{PS})}} - e^{-\frac{\alpha}{2}} \sum_{k=0}^{m-2} \frac{1}{k!} \left(\frac{\alpha \cdot \gamma_{PS}}{2(1+\gamma_{PS})}\right)^k. \end{aligned}$$

transmission power Ps and the detection threshold α based on the knowledge of the channel parameters ($\gamma_P, \gamma_S, \gamma_{PS}, \gamma_{SP}$) and the system parameters (β_P, β_S, λ_P) to best accomplish two conflicting goals: a) making its activity transparent to the primary link and b) maximizing its own stable throughput μ_S[3] (packets/ slot). We follow the approach presented in [1], where the constraint on transparency is guaranteed by imposing the stability of the queue of the primary transmitter (see Sec. 4 for a discussion about delay constraints). Moreover, we remark that the average channel parameters (γ_P, γ_S, γ_{PS}, γ_{SP}) are assumed to be perfectly known[4] by the secondary transmitter, under the premise that, before starting transmission, the secondary node has estimated these parameters during an observation period of a few time slots[5].

Extending the analysis of [1] to the considered scenario, where we optimized both transmission power Ps and the detection threshold α, we obtain the following result.

Proposition 1: Given the channel parameters (γ_P, γ_S, γ_{PS}, γ_{SP}) and the system parameters (β_P, β_S, α, m), under the constraint that the stability of the queue of the primary user is preserved, the maximum stable throughput at the secondary node is obtained by solving the following optimization problem:

$$\max_{P_S,\alpha} \mu_S(P_S,\alpha) \tag{2}$$
$$\text{s.t.} \begin{cases} P_S \leq 1 & \text{if } \lambda_P \leq \bar{\lambda}_P(\alpha) \\ P_S \leq \frac{N_P}{D_P} \times \left(\frac{\gamma_P/\beta_P}{\gamma_{SP}}\right) & \text{if } \lambda_P > \bar{\lambda}_P(\alpha) \end{cases}$$

where we have defined for simplicity of notation $N_P = \exp\left(-\frac{\beta_P}{\gamma_P}\right) - \lambda_P$ and $D_P = \lambda_P - P_d(\alpha)\exp\left(-\frac{\beta_P}{\gamma_P}\right)$. The throughput of the secondary

$$\begin{aligned} \mu_S(P_S,\alpha) &= \left(1 - \frac{\lambda_P}{\mu_P(P_S,\alpha)}\right)\exp\left(-\frac{\beta_S}{\gamma_S P_S}\right) \\ &\quad \times (1 - P_{fa}(\alpha)), \end{aligned} \tag{3}$$

depends on the throughput of the primary:

$$\mu_P(P_S,\alpha) = \mu_P^{\max}\frac{\frac{\gamma_P}{\beta_P} + P_S P_d(\alpha)\gamma_{SP}}{\gamma_{SP}P_S + \frac{\gamma_P}{\beta_P}}. \tag{4}$$

Moreover, the maximum value of the primary arrival rate at which the secondary can use maximum power is:

$$\bar{\lambda}_P(\alpha) = \mu_P^{\max}\frac{\frac{\gamma_P}{\beta_P} + P_d(\alpha)\cdot\gamma_{SP}}{\gamma_{SP} + \frac{\gamma_P}{\beta_P}} \tag{5}$$

and $\mu_P^{\max} = 1 - P_{out,P} = \exp(-\frac{\beta_P}{\gamma_P})$ corresponds to the maximum stable throughput of the primary user in absence of the secondary (see [1] for further details).

Proof: based on the concept of *dominant system* introduced in [10] and easily obtained from the proof of Propositions 1, 2 in [1].

In order to get insight into system performance, fig. 2 shows the optimal power P_S, the optimal threshold α and the maximum stable throughput $\mu_S(P_S,\alpha)$ obtained from the solution of the optimization problem (2)[6] versus the selected arrival rate of the primary transmitter λ_P[7] (parameters values: β_P = 4 dB, β_S = 4 dB, γ_P = 4 dB, γ_S = 10 dB, γ_{PS} = 10 dB, γ_{PS} = 10 dB, m = 5). As it can be seen, the optimum threshold α decreases as λ_P increases: for increasing λ_P, it becomes imperative for the secondary to be able to detect the primary activity with small missed detection probability in order not to create excessive interference on the primary transmission. In fact, if this condition was not satisfied, the channel would be permanently used for retransmissions by the primary, not leaving any transmission opportunity for the secondary.

3. ADDING RELAYING CAPABILITY AT THE COGNITIVE NODE

In this section, we reconsider the model studied in the previous section by including the possibility that the secondary transmitter acts as a *transparent* relay for the primary transmitter, as explained in Sec. 1. Accordingly, the secondary transmitter stores in its queue $Q_{PS}(t)$ packets of the primary that have not been successfully received by the intended destination but have been correctly decoded at the secondary. As soon as the secondary senses an idle slot, it chooses to transmit from queue $Q_{PS}(t)$ with probability ε and from the queue which stores its own packets, $Q_S(t)$, with probability $(1-\varepsilon)$.

3.1. System analysis

Here we assume that the secondary has the degrees of freedom to choose its transmission power $P_S \leq 1$, detection threshold α and scheduling probability ε towards the goal discussed in Sec. 2.3. Extending the analysis of [1] to the scenario at hand, we obtain the following result.

Proposition 2: Given the channel parameters (γ_P, γ_S, γ_{PS}, γ_{SP}) and the system parameters (β_P, β_S, λ_P, m), under the assumption that the stability of the queue of the primary user is preserved, the maximum stable throughput at the secondary node is obtained by solving the following optimization problem:

$$\max_{P_S,\alpha} \mu_S^{rel}(P_S,\alpha) \tag{6}$$
$$\text{s.t.} \begin{cases} P_S \leq 1 & \text{if } \lambda_P \leq \bar{\lambda}_P^{rel}(\alpha) \\ P_S \leq \frac{N_P + \Delta\mu_P(\alpha)}{D_P - \Delta\mu_P(\alpha)}\left(\frac{\gamma_P/\beta_P}{\gamma_{SP}}\right) & \text{if } \lambda_P > \bar{\lambda}_P^{rel}(\alpha) \end{cases}$$
$$\varepsilon = \frac{\lambda_P\left(1-\exp\left(-\frac{\beta_P}{\gamma_P}\right)\right)\exp\left(-\frac{\beta_P}{\gamma_{PS}}\right)}{\left(\mu_P^{rel}(P_S,\alpha)-\lambda_P\right)\exp\left(-\frac{\beta_P}{\gamma_{SP}P_S}\right)(1-P_{fa}(\alpha))} < 1$$

[3] The maximum stable throughput of the original system coincides with the average departure rate of the corresponding dominant system [10].

[4] The analysis of the sensitivity of the system performance to estimation errors is outside the scope of this paper.

[5] We remark that, while power gains ($\gamma_{SP}, \gamma_{PS}, \gamma_S$) can be estimated directly by the secondary node, gain γ_P can be inferred by observing the number of ACK/NACK messages sent by the primary receiver to the primary transmitter.

[6] The problem (2) (and similar problems studied in this paper) is not convex, but shows in our simulations to be well-behaved, having a global maximum, which can be reached by an optimization gradient-based routine with different initial conditions in order not to be trapped in local maximum points.

[7] In all the figures of this paper, the maximum value of λ_P taken into account corresponds to the maximum stable throughput perceived by the primary user, that is, the previously defined quantity $\mu_P^{\max}$.

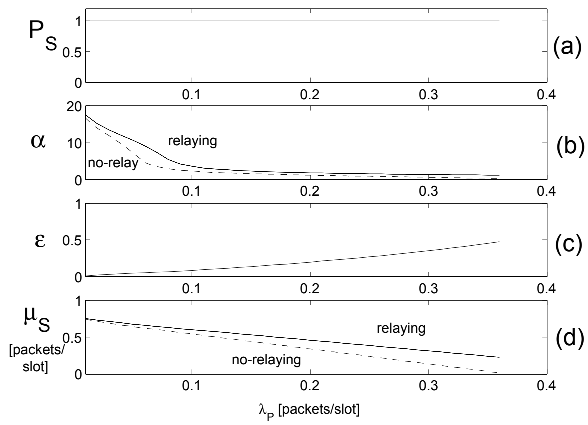

Fig. 2. Optimal power P_S, detection threshold α, scheduling probability ε and maximum stable throughput μ_S obtained from Proposition 1 and 2 versus the arrival rate selected by the primary node λ_P (β_P = 4 dB, β_S = 4 dB, γ_P = 4 dB, γ_S = 10 dB, $\gamma_{PS} = \gamma_{SP}$ = 10 dB, $m = 5$).

where the throughput of the secondary node reads:

$$\begin{aligned}\mu_S^{rel}(P_S,\alpha) \quad = \quad & \left[\frac{\mu_P^{rel}(P_S,\alpha)-\lambda_P}{\mu_P^{rel}(P_S,\alpha)}\exp\left(-\frac{\beta_P}{\gamma_{SP}P_S}\right)\right. \\ & \times\left(1-P_{fa}\left(\alpha\right)\right)-\frac{\lambda_P}{\mu_P^{rel}(P_S,\alpha)}(1-\mu_P^{\max}) \\ & \left.\times\exp\left(-\frac{\beta_P}{\gamma_{PS}}\right)\right]\exp\left(\frac{\beta_P}{\gamma_{SP}P_S}-\frac{\beta_S}{\gamma_S P_S}\right),\end{aligned} \tag{7}$$

which depends on the primary throughput $\mu_P^{rel}(P_S,\alpha)$=$\mu_P(P_S,\alpha)$ + $\Delta\mu_P(\alpha)$, where $\mu_P(P_S,\alpha)$ is the throughput with no relaying (4) and $\Delta\mu_P(\alpha)$ is the gain due to relaying:

$$\Delta\mu_P(\alpha) = P_d(\alpha)\exp\left(-\frac{\beta_P}{\gamma_{PS}}\right)(1-\mu_P^{\max})\,. \tag{8}$$

Moreover, we have $\bar{\lambda}_P^{rel}(\alpha) = \bar{\lambda}_P(\alpha)+\Delta\mu_P(\alpha)$ (recall (5)).

Proof: based on the concept of *dominant system* introduced in [10] and easily obtained from the proof of Propositions 3, 4 in [1].

Fig. 2 compares the performance of the cognitive interference channel for the cases of relaying (Proposition 2) and no relaying (Proposition 1) in terms of optimum power P_S, optimum probability ε, optimum threshold α and the maximum stable throughput $\mu_S^{rel}(P_S,\alpha)$, for the same selection of system and channel parameters as in Sec. 2.3. For both cases, in this example, maximum power $P_S = 1$ is optimal. Moreover, it is interesting to notice the relevant advantages of relaying for sufficiently large λ_P in terms of stable throughput. Finally, it can be seen that the relaying allows the secondary to set a larger threshold α, thus exploiting on average more transmission opportunities.

Relaying from the cognitive transmitter according to the simple protocol studied so far is not necessarily advantageous when the channels between primary and secondary are not good enough to support the traffic relayed on behalf of the primary. Fig. 3 shows the maximum throughput of the secondary for a fixed value of the throughput of the primary $\lambda_P = \mu_P^{\max}$ versus increasing values of the channel power gains $\gamma_{SP} = \gamma_{PS}$[8].We used the following values for the other system and channel parameters: β_P = 4dB, β_S = 4dB, γ_P = 7dB, γ_S = 10dB, m = 5. For primary-secondary channel gains γ_{SP} and γ_{PS} sufficiently larger than the direct primary channel gain γ_P = 7 dB, the secondary is able to relay traffic from the primary efficiently, thus creating transmission opportunities for its own traffic and increasing its own throughput. If, however, this condition is not satisfied, the secondary transmitter is not able to deliver the extra-traffic coming from the primary. As a consequence, for small values of γ_{SP} and γ_{PS}, no feasible solution for the optimization problem (6) exists, and thus the throughput of the secondary is zero. The next section discusses an effective solution to this problem based on packet acceptance control at the cognitive node.

4. RELAYING AND PACKET ACCEPTANCE CONTROL

As discussed in the example of fig. 3, the protocol studied in the previous section (and in [1] but without optimized detection threshold α) suffers from degraded performance in a situation where the secondary transmitter is not able to handle the extra-traffic coming from the primary. Towards the goal of alleviating this problem, we assume herein that the secondary transmitter is able to select not only its transmitting power P_S, the detection threshold α and the probability ε, but also the fraction f of packets coming from the primary transmitter that it is willing to accept. The rationale of this choice lies in the attempt to give the secondary node the possibility to better manage situations of congestion of queue $Q_{PS}(t)$. The system model then modifies with respect to Sec. 3 in that the secondary transmitter stores in its queue $Q_{PS}(t)$ a packet correctly received from the primary (but erroneously decoded at the primary destination) with probability f (and consequently sends an ACK message to the primary).

4.1. System analysis

Extending Proposition 2 to the case of relaying with packet acceptance control is relatively straightforward in the light of the analysis of [1]. In particular, the result can be stated as an optimization over parameters P_S, α, f similarly to (6) with the following differences: (*i*) the gain in the primary throughput $\Delta\mu_P(\alpha)$ (8) and the scheduling probability ε have to be multiplied by the fraction of packets accepted by the secondary f; (*ii*) in the secondary throughput (7), the second term in the square brackets gets multiplied by f.

Here we complete the example of fig. 3 discussed in the previous section by considering the performance of the packet acceptance scheme. It can be seen that, even in the range of small values of the channels γ_{SP} and γ_{PS} ($< \gamma_P$), packet acceptance control enables a non-zero (albeit small) secondary throughput, thus showing that the queue $Q_{PS}(t)$ does not overflow as for the basic relaying protocol studied in the previous section. Finally, as expected, if channels γ_{SP} and γ_{PS} are large enough, the optimal fraction of accepted packets tends to one and the scheme with packet acceptance control has the same performance as the basic scheme.

[8]Notice that, from Proposition 1 (see (3)), for $\lambda_P = \mu_P^{\max}$ the maximum stable throughput μ_S of the case of no-relaying is equal to 0. Therefore, fig. 3 can be interpreted as showing the gain in terms of maximum stable throughput for the relaying case with respect to the no-relaying case.

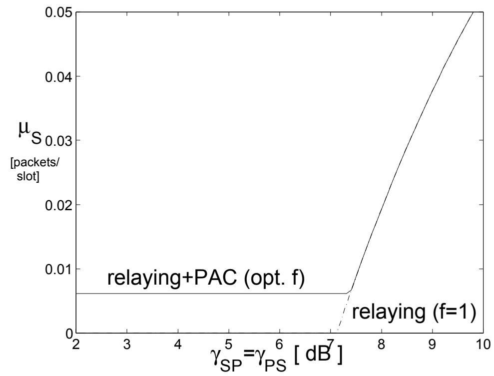

Fig. 3. Maximum throughput of the secondary user μ_S for a fixed $\lambda_P = \mu_P^{\max}$ versus the value of the channel parameters γ_{SP} and γ_{PS} (β_P = 4 dB, β_S = 4 dB, γ_P = 7 dB, γ_S = 10 dB, m = 5)

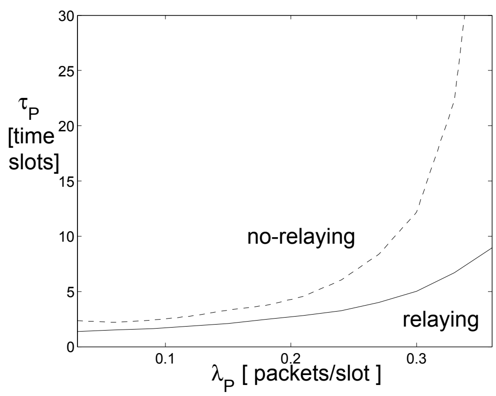

Fig. 4. Average delay of the primary packets τ_P versus the throughput selected by the primary node λ_P for the no-relaying case and the relaying case (λ_S = 0.1, β_P = 4 dB, β_S = 4 dB, γ_P = 4 dB γ_S = 10 dB, $\gamma_{PS} = \gamma_{SP}$ = 10 dB, m =5)

5. DELAY-SENSITIVE APPLICATIONS

In the previous sections, transparency of the activity of the secondary to the primary was defined in terms of the stability of the primary queue. Therefore, the fact that the primary might experience very large delays as a result of the secondary transmissions was not accounted for. In this section, we study via numerical simulation the performance in terms of delay of the protocols discussed above. We then briefly (for space limitation) propose a solution to satisfy delay constraints.

We assume Poisson distributed incoming traffic both at the primary and at the secondary nodes. Fig. 4 compares the average delay τ_P of the primary packets versus the primary arrival rate λ_P for the relaying case and the no-relaying case, showing the relevant advantages arising from the use of the relaying protocol in situations characterized by good channels γ_{PS} and γ_{SP} (parameters are as in Sec. 2.3 with λ_S = 0.1).

While in general relaying enables better performance in terms of delay, there are no guarantees that a given delay constraint will be satisfied by the primary packets. A solution to this problem would be to run the optimization problem at the secondary transmitter by adding a constraint on the delay of the primary packets. The problem is that, even assuming independent identically distributed Bernoulli packet arrivals, the departure processes are not stationary due to the interactions between the queues. As a consequence, the primary queue $Q_P(t)$ needs to be modelled as a M/G/1 system (notice that in the analysis of stability carried out in the rest of the paper, non-stationarity of departure processes was handled by using the dominant system concept from [10]). From some preliminary results, it appears that the packet acceptance control scheme studied in the previous section, with its added degree of freedom given by the fraction of packet to be accepted by the secondary, is a particularly suitable candidate for this application.

6. CONCLUSIONS

In this paper, the maximization of the stable throughput of the secondary node, under the constraints of transparence imposed by cognitive radio, has been studied by assuming that the secondary can possibly act as a relay for the primary traffic. Performance advantages, in terms of secondary stable throughput, of optimal primary detection (sensing) and packet acceptance control at the secondary node have been investigated. Moreover, delay performance of the presented protocols has been studied via numerical simulation.

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