Stability analysis of the cognitive interference channel

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***Abstract*— A scenario with two single-user links, one licensed to use the spectral resource (primary) and one unlicensed (secondary), is considered (cognitive interference channel). In accordance to the cognitive radio principle, whereby the activity of the secondary link should not interfere with the performance of the primary, the unlicensed transmitter accesses the channel only when sensed idle. In this paper, the maximum stable throughput of the cognitive link (in packets/slot) is derived for a fixed throughput selected by the primary link by assuming: 1) sensing errors due to fading at the secondary link; 2) power allocation at the secondary transmitter based on long-term measurements.**

I. Introduction

Based on the evidence that fixed (licensed) resource allocation yields an inefficient use of the radio spectrum, the cognitive radio paradigm prescribes the co-existence of licensed and unlicensed spectrum access [1]. In particular, primary (lincensed) terminals are granted access to the spectral resource any time, while the secondary (unlicensed or cognitive) users seek trasmission opportunities by capitalizing on the idle periods of primary users. The main requirement is that the activity of cognitive nodes should be "transparent" to primary links.

In this paper, we consider the cognitive interference channel in fig. 1, that consists in two single-user links, one licensed and one unlicensed. The framework is inspired by the recent works [2] [3], where the study of this channel is pursued from an information theoretic standpoint, by assuming that the cognitive transmitter has prior information about the codeword transmitted by the primary. In contrast, in this work, we model the effect of random packet arrivals and explicitly take into account the effect of measurement errors at the cognitive nodes.

To elaborate, transmitters are assumed to be equipped with infinite queues and time is slotted[1]. At the beginning of each slot, the cognitive node senses the channel and, if detected idle, transmits a packet (if it has any in queue). Unfortunately, as discussed in [4], detection of the primary activity may incur in errors due to impairments on the wireless fading channel, thus causing possible interference from the secondary to the primary link. Since the cognitive principle is based on the idea that the presence of the secondary link should be "transparent" to the primary, appropriate countermeasures should be adopted at the secondary nodes. In particular, here we assume that the secondary transmitter is able to adjust its transmitted power according to the average channel gains of the system in order not to affect the performance of the primary node.

[1]This implies that the cognitive nodes are able to infer the timing of the primary link from the received signal during the observation phase [1].

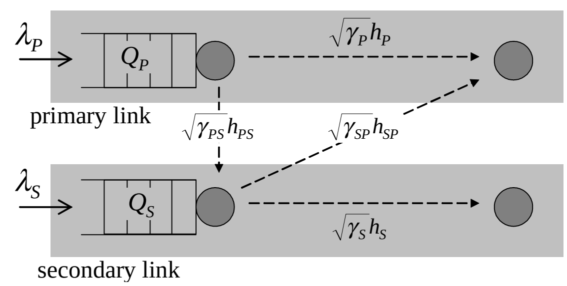

Fig. 1. MAC and physical layer view of a simple cognitive scenario with one primary and one secondary single-link connections sharing the same spectral resource (cognitive interference channel).

With reference to fig. 1, the primary link selects an average throughput λ_P (in packets/slot) based on the knowledge of the average channel gain γ_P on the direct link, being oblivious to the presence of cognitive nodes. The secondary transmitter learns the average channel gains of the system $(\gamma_P, \gamma_S, \gamma_{PS}, \gamma_{SP})$ and the average throughput λ_P selected by the primary during the observation phase. The question we wish to answer here is: *what is the maximum average throughput that the secondary link can sustain while guaranteeing the stability of the system?* In answering this question we assume that the secondary node is able to appropriately control its transmitted power according to the discussed available side information. Notice that "transparency" of the cognitive node to the primary user is here defined in terms of *stability* of the queue of the primary user. That is, as a result of the activity of the secondary, the primary node is guaranteed that its queue will remain stable.

II. System model and problem formulation

We consider the scenario in fig. 1, where a single-link primary communication is active and a secondary (cognitive) single link is interested in employing the spectral resource whenever available. The analysis is based on a model that encompasses both physical layer parameters and MAC dynamics as follows.

A. MAC layer model

Both primary and secondary transmitting nodes have a buffer of infinite capacity to store incoming packets. Time is slotted and transmission of each packet takes one slot (all packets have the same number of bits). The packet arrival processes at each node are independent and stationary with mean λ_P [packets/slot] for the primary user and λ_S [packets/slot] for the cognitive (see fig. 1). Due to impairments on the radio channel (fading, see below), a packet can be received in error by the intended destination, which requires retransmission. Notice that the overhead for transmission of ACKnowledgement (ACK)/ Not-ACKnowledgment (NACK) messages is not modelled in the analysis.

According to the cognitive principle, the primary link employs the channel whenever it has some packets to transmit in its queue. On the other hand, the secondary (cognitive) transmitter senses the channel in each slot and, if it detects an idle slot, transmits a packet (if there is any) from its queue. Notice that this assumes that the slot is sufficiently long so as to allow an appropriate detection time interval for the cognitive node. As discussed below, because of reception impairments due to fading, the secondary transmitter may incur in errors while detecting the presence of the primary user.

B. Physical layer model

With reference to fig. 1, radio propagation between any pair of nodes is assumed to be affected by *independent stationary Rayleigh* fading channels $h_i(t)$ with $E[|h_i(t)|^2] = 1$ (t denotes time and runs over time-slots). The average channel power gain (due to shadowing and path loss) is denoted as γ_i, where i reads "P" for the primary connection, "S" for the secondary, "SP" for the channel between secondary transmitter and primary receiver and "PS" for the channel between primary transmitter and secondary receiver.

The primary node transmits with normalized power $P_P = 1$ and, without loss of generality, the noise power spectral density at all receivers is also normalized to 1. The power transmitted by the secondary node (when active) is $P_S \leq 1$. Transmission of a given packet is considered successful if the instantaneous received signal-to-noise ratio (SNR) $\gamma_i|h_i(t)|^2 P_i$ is above a given threshold β_i, that is fixed given the choice of the transmission mode. Therefore, the *probability of outage* (unsuccessful packet reception) on the primary or secondary link reads (i equals "P" or "S")

$$\mathrm{P}_{out,i} = \mathrm{P}[\gamma_i|h_i(t)|^2 P_i < \beta_i] = 1 - \exp\left(-\frac{\beta_i}{\gamma_i P_i}\right). \quad (1)$$

Notice that the primary and secondary links can in general employ transmission modes with different signal-to-noise ratio requirements, $\beta_P \neq \beta_S$.

The cognitive node is able to correctly detect the transmission of the primary user if the instantaneous SNR $\gamma_{PS}|h_{PS}|^2$ is larger than a threshold α (recall that $P_P = 1$). It follows that the probability of error in the detection process is

$$\mathrm{P}_e = \mathrm{P}[\gamma_{PS}|h_{PS}(t)|^2 < \alpha] = 1 - \exp\left(-\frac{\alpha}{\gamma_{PS}}\right). \quad (2)$$

We assume that whenever the secondary node is able to decode the signal of the primary, it is also able to detect its presence, i.e., $\alpha < \beta_P$. Moreover, it is assumed that whenever the primary user is not transmitting, the secondary transmitter is able to detect an idle slot with zero probability of error. This assumption is reasonable in the scenario at hand where interference from other systems is assumed to be negligible.

C. Problem formulation

The analysis presented in this paper assumes that the secondary transmitter is able to select its transmission power $P_S \leq 1$ based on the statistics of the channels $(\gamma_P, \gamma_S, \gamma_{PS}, \gamma_{SP})$ and the system parameters $(\alpha, \beta_P, \beta_S, \lambda_P)$ towards the following two conflicting goals: (*i*) making its activity "transparent" to the primary link (more details below); (*ii*) maximizing its own stable throughput. Two remarks are in order:

1. "transparency" of the cognitive node to the primary user is here defined in terms of *stability* of the queue of the primary user. That is, as a result of the activity of the secondary, the primary node is guaranteed that its queue will remain stable, but no constraints are imposed on the increase in the average delay experience by the primary;
2. knowledge of the (average) channel parameters $(\gamma_P, \gamma_S, \gamma_{PS}, \gamma_{SP})$ at the cognitive transmitter is assumed under the premise that in the assumed stationary fading scenario, the cognitive node will have enough time to infer these parameters during the observation phase of the cognitive cycle.

III. Stable throughput of the cognitive node

In this Section, we investigate the maximum throughput (i.e., average arrival rate) λ_S that can be sustained by the secondary node for a given (fixed) throughput λ_P selected by the primary node, provided that the system remains stable. In other words, the primary user selects its own arrival rate λ_P ignoring the presence of a secondary node; it is then the task of the cognitive user to select its transmission mode (here the power P_S) in order to exploit as much as possible the idle slots left available by the primary activity while not affecting stability of the system.

A. Some definitions

Stability is defined as the state where all the queues in the system are stable. A queue is said to be stable if and only if the probability of being empty remains nonzero for time t that grows to infinity:

$$\lim_{t\to\infty} \mathrm{P}[Q_i(t) = 0] > 0, \quad (3)$$

where $Q_i(t)$ denotes the unfinished work (in packets) of the ith queue at time t. For a more rigorous definition of stability, the reader is referred to [6]. If *arrival and departure rates of a queuing system are stationary*, then stability can be checked by using *Loynes' theorem* [5]. This states that, under the said assumption, if the average arrival rate λ_i is less than the average departure rate μ_i, $\lambda_i < \mu_i$, then the ith queue is stable; on the other hand, if the average arrival rate λ_i is greater than the average departure rate μ_i, the queue is unstable; finally, if $\lambda_i = \mu_i$, the queue can be either stable or unstable. Whenever the Loynes' theorem is applicable, we define the average departure rate μ_i as the *maximum stable throughput* of the ith queue.

B. The point of view of the primary user

To elaborate, let us consider the system from the point of view of the primary transmitter. According to the cognitive principle, the primary link is unaware of the presence of a secondary node willing to use the bandwidth whenever available. Therefore, as far as the primary node is concerned, the system consists of a single queue (its own), characterized by a stationary departure rate (due to the stationarity of the channel fading process $h_P(t)$) with average $\mu_P^{\max} = 1 - \mathrm{P}_{out,P} = \exp\left(-\frac{\beta_P}{\gamma_P}\right)$. Moreover, by the Loynes' theorem, the rate $\mu_P^{\max}$ is the maximum stable throughput as "perceived" by the primary user. In other words, the primary user is allowed to select any rate λ_P that satisfies:

$$\lambda_P < \mu_P^{\max} = \exp\left(-\frac{\beta_P}{\gamma_P}\right). \quad (4)$$

C. The ideal system (no measurement errors)

In an ideal system, the cognitive link does not incur in any error while detecting the activity of the primary user. Therefore, it can access the channel in idle slots without causing any interference to the primary link, and the queues at the two transmitters are non-interacting. It follows that the departure rate at the secondary transmitter is stationary due to the stationarity of the channel process $h_S(t)$, and has average equal to $\mu_S^{\max}(P_S) = (1 - \mathrm{P}_{out,S}) \cdot \mathrm{P}[Q_P(t) = 0]$, where the second term enforces the constraint that the secondary node accesses the channel only when the primary does not have any packet in its queue. Recalling Little's theorem, we have $\mathrm{P}[Q_P(t) = 0] = 1 - \lambda_P/\mu_P^{\max}$, which from (1) yields

$$\mu_S^{\max}(P_S) = \exp\left(-\frac{\beta_S}{\gamma_S P_S}\right)\left(\frac{\mu_P^{\max} - \lambda_P}{\mu_P^{\max}}\right). \quad (5)$$

Therefore, in the ideal case, the maximum throughput of the secondary link is achieved for transmitted power P_S equal to its maximum, $P_S = 1$. Furthermore, it is a fraction of the "residual" throughput $(\mu_P^{\max} - \lambda_P)/\mu_P^{\max}$ left available by the activity of the primary link according to the probability of outage on the secondary link.

D. The real system

In the real system, the cognitive node senses the channel at each slot and, if it measures no activity from the primary, it starts transmitting with power $P_S \leq 1$ (provided that there is at least one packet in queue). However, due to errors in the detection process, the secondary node starts transmitting (with the same power P_S) even in slots occupied by the primary transmission with probability P_e in (2) (again, provided that there is at least one packet in its queue). This causes interference to the communication on the primary link, which in turns reduce the actual throughput of the primary. From this discussion, it is apparent that the queuing systems of primary and secondary transmitters are interacting, and, therefore, stationarity of the departure rates cannot be guaranteed making the Loynes' theorem not applicable [6] [7].

Let us first consider the maximum power P_S that the cognitive node is allowed to transmit in order to guarantee stability of the queue of the primary.

Proposition 1: Given the channel parameters $(\gamma_P, \gamma_{PS}, \gamma_{SP})$ and system parameters $(\alpha, \beta_P, \lambda_P)$:

- if $\lambda_P < \mu_P^{\max} \exp\left(-\alpha/\gamma_{PS}\right)$, the secondary user can employ any power P_S without affecting the stability of the queue of the primary node, and in particular we can set P_S equal to its maximum, $P_S = 1$;
- if $\mu_P^{\max} \exp\left(-\alpha/\gamma_{PS}\right) \leq \lambda_P < \mu_P^{\max}$, the maximum power that the cognitive node can employ is

$$P_S < \left(\frac{\mu_P^{\max} - \lambda_P}{\lambda_P - \mu_P^{\max}\exp\left(-\frac{\alpha}{\gamma_{PS}}\right)}\right)\frac{\gamma_P/\beta_P}{\gamma_{SP}}. \quad (6)$$

Sketch of the proof (see Appendix-A): due to the interaction between the queues at the primary and secondary transmitting nodes (see [6] [7]), the Loynes' theorem cannot be directly employed to investigate stability of the system. In order to overcome the problem, following [6], we can study a transformed system, referred to as *dominant*, that has the same stability properties as the original system and, at the same time, presents non-interacting queues. In the setting at hand, the dominant system can be constructed by modifying the original setting described in Sec. II in the following simple way: if $Q_S(t) = 0$, the secondary node transmits "dummy" packets whenever it senses an idle channel, thus continuing to possibly interfere with the primary user irrespective of whether its queue is empty or not. By using the same arguments of [7], it can be easily shown that this dominant system is stable if and only if the original system is: in fact, on one hand, the queues of the dominant system have always larger size than the ones of the original system (thus if the dominant system is stable, the original is) and, on the other, under saturation the probability of sending a "dummy" packet in the dominant system is zero and the two systems are indistinguishable (therefore, if the dominant system is unstable, the original is). As shown in Appendix-A, in the dominant system the departure rates are stationary processes and thus we can employ the Loynes' theorem to draw conclusions about the stability of the original system.

As a direct consequence of Proposition 1, the secondary can employ its maximum power $P_S = 1$ for $\lambda_P < \bar{\lambda}_P$ where

$$\bar{\lambda}_P = \mu_P^{\max}\left[\frac{\gamma_P/\beta_P + \exp\left(-\frac{\alpha}{\gamma_{PS}}\right)\gamma_{SP}}{\gamma_{SP} + \gamma_P/\beta_P}\right]. \quad (7)$$

Fig. 2 shows the maximum power P_S allowed to the secondary user (6) versus the throughput selected by the primary user λ_P for $\beta/\gamma_P = -5dB$ (which implies $\mathrm{P}_{out,P} = 0.27$), $\gamma_{SP} = 10$, 15, $20dB$ and $\alpha/\gamma_{PS} = -5dB$ ($\mathrm{P}_e = 0.27$). Notice that the maximum rate that the primary user can select is $\mu_P^{\max} = 0.73$ in (4), and that the primary rate $\bar{\lambda}_P$ (7) at which the secondary node has to reduce its power as compared to 1 reduces for increasing γ_{SP}. The sensitivity of $\bar{\lambda}_P$ to the detection error probability is shown in fig. 3, where the ratio $\bar{\lambda}_P/\mu_P^{\max}$ is plotted versus α/γ_{PS} again for $\gamma_{SP} = 10$, 15, $20dB$: for $\mathrm{P}_e \to 1$ (increasing α/γ_{PS}) this ratio tends to $\gamma_P/\beta_P/(\gamma_{SP} + \gamma_P/\beta_P)$, whereas for $\mathrm{P}_e \to 0$ (decreasing α/γ_{PS}) the ratio tends to 1 and the cognitive node is allowed to use its maximum power for any λ_P in (4).

Let us now turn to the study of the queuing process at the cognitive node. We are interested in solving the original problem of deriving the maximum throughput sustainable by the secondary node under the constraint that the system is stable. As shown below, the problem reduces to an optimization over the transmitted power P_S (under the constraint set by Proposition 1). In fact, there exists an inherent trade-off in the choice of P_S: on one hand, increasing P_S increases the interference on the primary link, which limits the probability of transmission opportunities for the cognitive node; on the other, increasing P_S enhances the probability of correct reception on the secondary link.

Proposition 2: Given the channel parameters $(\gamma_P, \gamma_S, \gamma_{PS}, \gamma_{SP})$ and system parameters $(\alpha, \beta_P, \beta_S, \lambda_P)$, under the assumption that the stability of the queue of the primary user is preserved ("transparency" of the cognitive node), the maximum stable throughput of the cognitive user is obtained by solving the following optimization problem:

$$\max_{P_S} \mu_S(P_S) \text{ (see (12))}$$
$$\text{s.t.} \begin{cases} P_S < \left(\frac{\exp\left(-\frac{\beta_P}{\gamma_P}\right) - \lambda_P}{\lambda_P - \exp\left(-\frac{\alpha}{\gamma_{PS}} - \frac{\beta}{\gamma_P}\right)} \right) \frac{\gamma_P/\beta_P}{\gamma_{SP}} & \text{if } \lambda_P \le \bar{\lambda}_P \\ P_S \le 1 & \text{if } \lambda_P > \bar{\lambda}_P \end{cases},$$

where $\bar{\lambda}_P$ is given by (7). Optimization problem above is convex and can be solved by using standard methods.

Proof: based on the analysis of the dominant system, see Appendix-B for details.

To get some insight into the analysis, fig. 4 shows the optimal transmitted power P_S and the corresponding maximum throughput μ_S for the cognitive node versus the selected throughput of the primary user λ_P in the same conditions as for fig. 2 and 3 ($\beta_P/\gamma_P = \beta_S/\gamma_S = -5dB$, $\gamma_{SP} = 5$, $15dB$ and $\alpha/\gamma_{PS} = -5dB$). In particular, the upper part of fig. 4 shows both the upper bound (6) (dashed lines) and the throughput-maximizing power P_S, whereas the lower part of the same figure shows the corresponding maximum throughput μ_S. As expected from (12), the maximum throughput μ_S decreases linearly with λ_P as long as the optimal P_S equals 1. For reference, the maximum stable throughput $\mu_S^{\max}(1)$ in (5) is shown, accounting for the case where no sensing errors occur at the cognitive link.

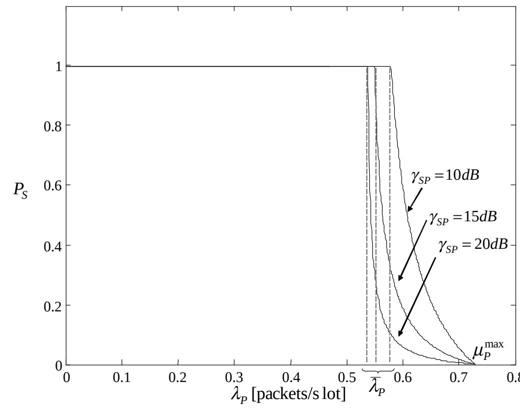

Fig. 2. Maximum power P_S allowed to the secondary user (Proposition 1) versus the throughput selected by the primary user λ_P for $\beta_P/\gamma_P = \alpha/\gamma_{PS} = \beta_S/\gamma_S = -5dB$, $\gamma_{SP} = 10$, 15, $20dB$.

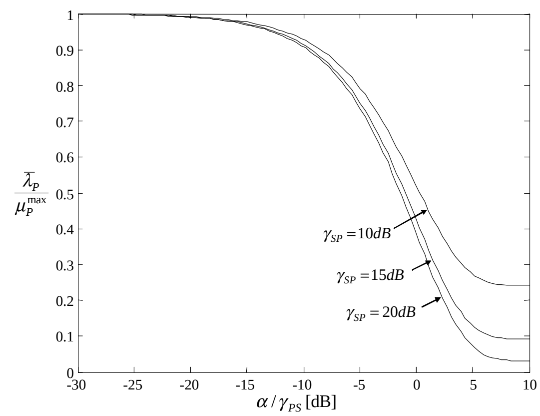

Fig. 3. Ratio $\bar{\lambda}_P/\mu_P^{\max}$ (7) versus the sensitivity of the detector of the primary activity at the secondary link α/γ_{PS} for $\beta_P/\gamma_P = -5dB$ and $\gamma_{SP} = 10$, 15, $20dB$.

IV. Appendix

A. Proof of Proposition 1

The queue size (in packets) of the primary evolves as $Q_P(t) = (Q_P(t-1) - X_P(t))^+ + Y_P(t)$, where $Y_P(t)$ is the *stationary* process representing the number of arrivals in slot t ($E[Y_P(t)] = \lambda_P$), and $X_P(t)$ is the departure process (to be proved to be stationary). Function $()^+$ is defined as $(x)^+ = \max(x, 0)$. By exploiting the definition of dominant system, the departure process can be written as:

$$X_P(t) = 1\{\mathcal{O}_D(t) \cap \mathcal{O}_P(t)\} + 1\{\mathcal{O}_D^c(t) \cap \mathcal{O}'_P(t)\}, \quad (8)$$

where $1\{\cdot\}$ is the indicator function of the event enclosed in the brackets; $\mathcal{O}_D(t)$ denotes the event that the cognitive node correctly identifies the ongoing activity of the primary user (and so it does not interfere), which happens with probability $1 - \mathrm{P}_e$ in (2); $\mathcal{O}_P(t)$ represents the event of a successful transmission by the primary user (assuming that the secondary does not interfere), which happens with probability $1 - \mathrm{P}_{out,P}$

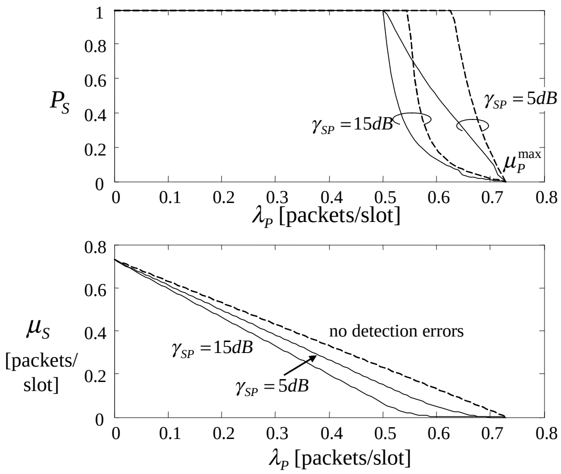

Fig. 4. Upper figure: upper bound on the power of the cognitive node P_S (dashed lines) and throughput-maximizing power P_S versus the throughput of the primary user λ_P; Lower figure: maximum throughput μ_S versus λ_P. As a reference, the maximum throughput in the case of no detection error is shown as dashed line ($\beta_P/\gamma_P = \beta_S/\gamma_S = -5dB$, $\gamma_{SP} = 5$, $15dB$ and $\alpha/\gamma_{PS} = -5dB$).

in (1); $\mathcal{O}_P^c(t)$ is the complement of $\mathcal{O}_P(t)$; $\mathcal{O}'_P(t)$ represents the event of a successful transmission by the primary user, assuming that the secondary interferes.which has probability $1-\mathrm{P}'_{out,P}$ (this can be calculated following [10]). From the definitions above, and using the stationarity of the channel gains, it is clear that the departure process $X_P(t)$ is stationary with mean given by $\mu_P(P_S) = E[X_P(t)] = (1-\mathrm{P}_e)\mu_P^{\max} + \mathrm{P}_e(1-\mathrm{P}'_{out,P})$. After substituting (1), (2) and $\mathrm{P}'_{out,P}$, the average departure rate results in (further details can be found in [11])

$$\mu_P(P_S) = \mu_P^{\max}\cdot\frac{\gamma_P/\beta_P + \exp\left(-\frac{\alpha}{\gamma_{PS}}\right)\gamma_{PS}P_S}{\gamma_P/\beta_P+\gamma_{PS}P_S}. \quad (9)$$

From stationarity of the processes involved, we can conclude that the primary queue is stable as long as $\mu_P(P_S) > \lambda_P$ (Loynes' theorem). For a given selected value of λ_P, this imposes a limitation on the power that the secondary user can employ, as stated in Proposition 1.

B. Proof of Proposition 2

The queue size (in packets) at the secondary node evolves as $Q_S(t) = (Q_S(t-1) - X_S(t))^+ + Y_S(t)$, where $Y_S(t)$ is the *stationary* process representing the number of arrivals in slot t ($E[Y_S(t)] = \lambda_S$), and $X_S(t)$ is the departure process (to be proved to be stationary). The latter can be expressed as $X_S(t) = 1\{\mathcal{A}_S(t)\cap\mathcal{O}_S(t)\}$, where $\mathcal{O}_S(t)$ is the event of a successful transmission by the secondary user (to its own receiver), whose probability is $1-\mathrm{P}_{out,S}$ in (1); $\mathcal{A}_S(t)$ denotes the event that slot t is available for transmission by the cognitive node. Since the queue of the primary user is stationary by construction, the slot availability process for the cognitive node (defined by $\mathcal{A}_S(t)$) is stationary [6]. Moreover, due to the considered MAC model, the probability of availability corresponds to the probability of having zero packets in the queue of the primary user (Little's theorem):

$$\mathrm{P}[\mathcal{A}_S(t)] = \mathrm{P}[Q_P(t)=0] = 1-\frac{\lambda_P}{\mu_P(P_S)}. \quad (10)$$

We can then conclude that $Y_S(t)$ is stationary with average

$$\mu_S(P_S) = E[Y_S(t)] = \mathrm{P}[Q_P(t)=0]\cdot(1-\mathrm{P}_{out,S}), \quad (11)$$

and, using the Loynes' theorem, the stable throughput for the secondary node is limited by the condition $\lambda_S < \mu_S(P_S)$. The last expression clearly shows the trade-off in the choice of the transmitted power P_S that was discussed above. In fact, from (1) and (9), we know that the two terms in (11) depend on the transmission power P_S in opposite ways, the first decreasing and the second increasing for increasing P_S. By plugging (10), (1) and (9) in (11), after some algebra we get

$$\begin{aligned}\mu_S(P_S) \;=\; & \left(\gamma_{SP}P_S\left[\mu_P^{\max}\exp\left(-\frac{\alpha}{\gamma_{PS}}\right)-\lambda_P\right]+\right. \quad (12)\\ & \left.+\gamma_P/\beta_P\left[\mu_P^{\max}-\lambda_P\right]\right)\cdot\\ & \cdot\frac{\exp\left(-\frac{\beta_S}{\gamma_S P_S}\right)}{\mu_P^{\max}(\gamma_P/\beta_P+\exp\left(-\frac{\alpha}{\gamma_{PS}}\right)\gamma_{SP}P_S)},\end{aligned}$$

which is easily shown to be concave in P_S. Having shown the stationarity of the involved processes, Proposition 2 is a direct consequence of Proposition 1 and Loynes' theorem.

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