Cognitive radio with secondary packet-by-packet vertical handover

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Abstract— **According to the commons model of cognitive radio, the activity of secondary (unlicensed) nodes is required to guarantee quality-of-service (QoS) constraints on the transmission of primary (licensed) terminals. Towards this goal, vertical handover between different radio interfaces is currently being investigated as a promising solution to enhance flexibility in unlicensed channel access. In this paper, we propose an analysis of cognitive radio with vertical handover capability in a simple scenario with one secondary node and two primary nodes that employ different radio interfaces with packet-based transmission. The maximum stable throughput of the secondary node is evaluated under maximum-delay QoS constraints on the primary activity as a function of system geometry, QoS constraints and sensing errors. Numerical results show the relevant advantages of optimal vertical handover in terms of the throughput of secondary nodes.**

I. Introduction

Cognitive radio is a debated new paradigm in wireless communications that promises to significantly improve the efficiency of spectrum usage of current systems by allowing the coexistence of licensed (primary) and unlicensed (secondary) users. Among different proposals, the most investigated so far is the so called commons model (see, e.g., [1] [2]). According to this framework, secondary users attempt to fill the "spectrum holes" left open by the primary activity under constraints on the interference caused on the primary links by secondary transmissions. The main challenge in this context is that of designing transmission protocols (encompassing power control at the physical layer, opportunistic transmission at the MAC layers, etc.) that are able to provide the necessary flexibility for spectrum access while still guaranteeing given quality-of-service (QoS) constraints on the primary activity.

In [4] and [5], a simple cognitive (commons model) interference channel composed of one primary and one secondary communication links has been studied and transmission policies that aim at maximizing the secondary maximum stable throughput have been proposed by accounting for random packet arrivals and sensing errors. While not considered in [4], further improvement in terms of maximum secondary throughput are expected to be achievable by adding the degree of freedom to access one among a number of available radio resources for transmission. In fact, an improvement in the flexibility in spectrum access leads to an increasing adaptability to different radio environmental conditions and primary traffic patterns. This promising technique is generally referred to as *vertical handover*.

The basic idea of vertical handover is that of dynamically redirecting communication streams of a given source to different radio interfaces (generally employed by different network standards) so as to guarantee given Quality of Service (QoS) requirements to the end user. The vertical mobility paradigm deserves research attention from many perspectives, accounting for issues related to the physical layer, mobile middleware, correct interfacing to the existing network protocols, mobility management solutions and wireless applications. This type of problem calls for a hybrid and cross-layer analytical approach in designing systems that can meet the requirements of managing the system capacity for various applications and mobility scenarios for a growing population of users. The most challenging task for system designers is to implement applications and software platforms that take full advantage of the diversity of the existing wireless networks and to provide means to deliver time sensitive data (such as voice or video) over a heterogeneous wireless network environment.

As an evidence of the research activity in the area of vertical handover, here we recall the ongoing standardization efforts within the 802.21 Working Group [6] and in the context of WINNER project [7] that aim at achieving integration between heterogeneous wireless networks. Previous work in this area has mainly focused on advantages arising from the employment of specific technical solutions at the network [8], transport [9] and application [10] layers to perform handover between common wireless standards for connection-based communications. On the contrary, in this paper, a *packet-by-packet* vertical handover will be studied in a simple cognitive-based scenario that allows to account for reasonable MAC and physical layer models. Specifically, one secondary user S and two primary users P_1 and P_2 that employ two different (orthogonal) radio interfaces (see fig. 1) are considered. The secondary node is assumed to be able to perform packet-by-packet vertical handover and power allocation based on the knowledge of long-term channel parameters (average channel powers) and QoS constraints selected by the primary users. We derive the maximum stable throughput achievable by the secondary node with optimal vertical handover and power allocation under maximum-delay QoS constraints on the primary activity.

II. System model

We consider the scenario shown in fig. 1, where there are two primary (licensed) independent communication links $P_1 - R_1$ and $P_2 - R_2$ that employ their respective radio resources (referred to as Ω_1 and Ω_2 respectively), and a secondary (cognitive) node S. The latter is able to run a packet-by-packet vertical handover policy and, thus, transmits its own packets whenever it is possible through either the radio interface Ω_1 towards the access point R_1 or the radio interface Ω_2 towards the access point R_2. In the envisioned scenario, access points R_1 and R_2 are connected to an, e.g. IP, network which routes the different packets to their intended destination(s). According to the principle of cognitive radio (commons model), the activity of the secondary node has to be transparent to the two primary communication links. Specifically, we consider that the activity of node S, which potentially interferes with transmissions from both P_1 and P_2, has to comply with some required QoS guarantees to the primary nodes P_1 and P_2. In particular, here we consider maximum delay constraints

$$D_i \leq D_{\max,i}, \ for \ i = 1, 2, \tag{1}$$

where D_i is the average delay (queueing plus transmission) experienced by the packets transmitted by the primary node P_i on the radio interface Ω_i.

With reference to fig. 1, we consider independent Rayleigh flat-fading channels $h_i(t)$, with $E[|h_i(t)|^2] = 1$, constant during a time-slot and independently varying over different time-slots. Each channel is characterized by an average channel gain (due to shadowing and path loss) denoted as γ_i, where i reads "$P,1$" for the link $P_1 - R_1$, "$SP,1$" for $S - R_1$, "$P,2$" for $P_2 - R_2$ and "$SP,2$" for $S - R_2$.

Transmitting nodes P_1, P_2 and S are equipped with infinite-length buffers to store the incoming packets. Transmission on the two (slot-synchronous) interfaces Ω_1 and Ω_2 is time-slotted and all the packets have the same length, equal to one time slot. The stochastic processes representing the number of packets stored in the queue of node P_1, P_2 and S read $Q_{P,1}(t)$, $Q_{P,2}(t)$ and $Q_S(t)$, respectively. The packets arrival processes at each node are independent and i.i.d. Bernoulli processes with mean λ_S [packets/slot] for the secondary user S and $\lambda_{P,1}$ and $\lambda_{P,2}$ [packets/slot] for the primary users P_1 and P_2 respectively.

Primary terminals P_1 and P_2 are assumed to transmit whenever they have packets in their queues $Q_{P,1}(t)$ and $Q_{P,2}(t)$ with powers $P_{P,1}$ and $P_{P,2}$ respectively. On the other hand, node S, which, according to the cognitive radio paradigm, is expected to employ the empty time-slots on any selected interface Ω_1 and Ω_2, runs the following transmission policy. The cognitive user S, if having at least one packet in its queue, performs the detection of the primary activity on the radio interface Ω_1 or Ω_2 with probability ϕ and $1 - \phi$, respectively, and transmits a packet only if it senses an idle slot in the considered spectral resource (i.e., whenever no transmission from node P_i, $i = 1, 2$, is detected).

Beside the handover probability ϕ, node S has the degree of freedom of choosing the transmitting powers $P_{S,1} \leq P_{P,1}$ and $P_{S,2} \leq P_{P,2}$ to employ on the interfaces Ω_1 and Ω_2 respectively. As detailed in Sec. IV, parameters $(P_{S,1}, P_{S,2}, \phi)$ have to be selected so as to counteract the following adverse conditions: (i) probability of missed detection $P_{e,i}$ and probability of false alarm $P_{fa,i}$ characterizing the detection of the activity of primary node P_i on interface Ω_i[1]; (ii) probability of outage of a packet sent to its intended destination, due to fading impairments on the channels. As for the latter, transmission of a packet on a given channel Ω_i is considered successful if the instantaneous signal-to-noise-plus-interference ratio is above a given threshold $\beta_{P,i}$, that is fixed given the choice of the transmission mode. In particular, the outage probability experienced by the primary node P_i reads:

$$P_{out,i} = \Pr\left[\gamma_{P,i} \left|h_{P,i}(t)\right|^2 P_{P,i} < \beta_{P,i}\right] = 1 - \exp\left(-\frac{\beta_{P,i}}{\gamma_{P,i} P_{P,i}}\right) \tag{2}$$

in case there is no interference from the secondary, while it reads:

$$P'_{out,i} = \Pr\left[\frac{\gamma_{P,i} \left|h_{P,i}(t)\right|^2 P_{P,i}}{1 + \gamma_{SP,i} \left|h_{SP,i}(t)\right|^2 P_{S,i}} < \beta_{P,i}\right] = 1 - \frac{\exp\left(-\frac{\beta_{P,i}}{\gamma_{P,i} P_{P,i}}\right)}{1 + \frac{\beta_{P,i}}{\gamma_{P,i} P_{P,i}} \gamma_{SP,i} P_{S,i}} \tag{3}$$

if the secondary node is interfering (see [4] for details). Finally, in case of an outage, the packet needs to be retransmitted (we assume that each destination notifies its respective source the correct or erroneous reception of each packet by means of ACK/NACK messages).

III. Problem definition

The goal of the cognitive node S is that of selecting the operating mode defined by the vertical handover policy parameter ϕ and the transmission powers $P_{S,1} \leq P_{P,1}$ and $P_{S,2} \leq P_{P,2}$ so as to maximize its own maximum stable throughput $\mu_S(P_{S,1},\ P_{S,2},\ \phi)$, given the channel and system parameters and the QoS constraints on the maximum average delay experienced by the packets transmitted by the primary users P_1 and P_2 specified in relationship (1) (by definition, any rate $\lambda_S \leq \mu_S$ guarantees stability of the queue $Q_S(t)$ at user S). Moreover, in order to allow this optimization, we consider that the cognitive node S is aware of the system parameters ($\beta_{P,1}$, $\beta_{P,2}$, $P_{e,1}$, $P_{e,2}$, $P_{fa,1}$, $P_{fa,2}$), receives the information on the parameters $D_{\max,1}$ and $D_{\max,2}$ from the access points R_1 and R_2, respectively and, finally, is able to estimate the long-term

[1]These generally depend on the selected detector and on the channel statistics.

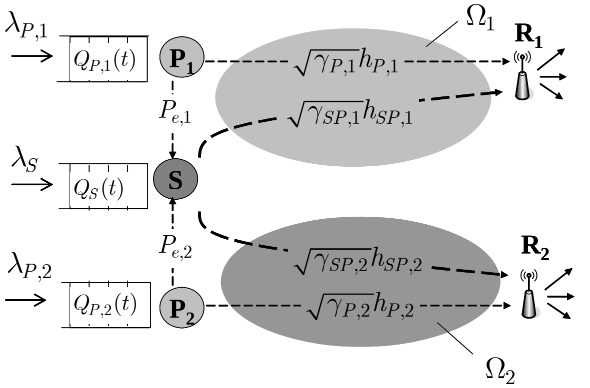

Fig. 1. A cognitive unlicensed node S has the capability to perform packet-by-packet vertical handover beween two radio interfaces (Ω_1 and Ω_2) served by access points R_1 and R_2, where two primary licensed nodes P_1 and P_2 are already active.

channel power gains ($\gamma_{P,1}$, $\gamma_{P,2}$, $\gamma_{SP,1}$, $\gamma_{SP,2}$). Notice that the channel power gain $\gamma_{P,i}$ might be estimated by evaluating the outage probability on the licensed link $P_i - R_i$, through observation of the number of ACK/NACK messages sent by the access point R_i to the primary node P_i.

IV. Analysis

Analysis of the delays in the system of fig. 1 requires, in principle, to find the joint stationary distribution of a three-dimensional Markov chain, where the state is defined by the number of packets in the queues $Q_S(t)$, $Q_{P,1}(t)$ and $Q_{P,2}(t)$. However, it is well known that even the simpler case of two interacting queues is analytically intractable except in some specific cases (see [11]). Therefore, in order to address the problem, here we consider a simplified system $\mathcal{S}$ in which the secondary node has always at least one packet (possibly "dummy") to transmit. This new system $\mathcal{S}$ is said to *dominate* the original one since, given that both of them are started with the same initial condition, the first has at least the same number of buffered packets in the queues as the second, for each time-slot on a realization-by-realization basis [12]. As a consequence of this, the modified system $\mathcal{S}$ provides upper bounds on the average delays experienced by the packets sent by the primary nodes P_1 and P_2 in the original system. The advantage of using this model is that, in the modified system, both $Q_{P,1}(t)$ and $Q_{P,2}(t)$ behave as two independent discrete-time monodimensional Markov chains, uncoupled from the stochastic process $Q_S(t)$. Therefore, the delays $\overline{D}_i$ ($i = 1, 2$) in the modified system are easily calculated as:

$$\overline{D}_i = \frac{1 - \lambda_{P,i}}{\mu_{P,i}(P_{S,i}, \phi) - \lambda_{P,i}}, \tag{4}$$

where $\mu_{P,i}(P_{S,i}, \phi)$ is the average departure rate from queue $Q_{P,i}(t)$ and is given by:

$$\begin{aligned} \mu_{P,i}(P_{S,i}, \phi) &= \Pr[\mathcal{O}_\rangle^\rfloor] \Pr[\mathcal{O}_\mathcal{P}] + \Pr[\mathcal{O}_\rangle] \\ &\quad \times \left(\Pr[\mathcal{O}_\mathcal{D}] \Pr[\mathcal{O}_\mathcal{P}] + \Pr[\mathcal{O}_\mathcal{D}^\rfloor] \Pr[\mathcal{O}'_\mathcal{P}] \right), \end{aligned} \tag{5}$$

where $\mathcal{O}_\rangle$ denotes the event that the cognitive user S performs detection on the interface Ω_i (and $\mathcal{O}_\rangle^\rfloor$ is its complement); $\mathcal{O}_\mathcal{P}$ represents the event of a successful transmission of a packet by the primary user P_i, which has probability equal to $P_{out,i}$ in (2); $\mathcal{O}_\mathcal{D}$ expresses the event of successful detection on the interface Ω_i; finally, $\mathcal{O}'_\mathcal{P}$ represents the event of a successful transmission by the primary user P_i, given that the cognitive user S is interfering, which has probability $P'_{out,i}$ in (3). Therefore, we obtain the following:

$$\begin{aligned} \mu_{P,1}(P_{S,1}, \phi) &= (1-\phi) \exp\left(-\frac{\beta_{P,1}}{\gamma_{P,1} P_{P,1}} \right) \\ &\quad + \phi \left((1 - P_{e,1}) \times \exp\left(-\frac{\beta_{P,1}}{\gamma_{P,1} P_{P,1}} \right) \right. \\ &\quad \left. + P_{e,1} \frac{\exp\left(-\frac{\beta_{P,1}}{\gamma_{P,1} P_{P,1}} \right)}{1 + \frac{\beta_{P,1}}{\gamma_{P,1} P_{P,1}} \gamma_{SP,1} P_{S,1}} \right). \end{aligned} \tag{6}$$

Similarly, $\mu_2(P_{S,2}, \phi)$ can be obtained from (6) by substituting the subscript "1" with "2" and the terms $(1 - \phi)$ and ϕ with ϕ and $(1 - \phi)$, respectively.

Since the delays of P_1 and P_2 in the original system satisfy $D_i \leq \overline{D}_i$ (with $i = 1, 2$), in order to obtain an analytically tractable problem, here we recast the QoS constraints $D_i \leq D_{\max,i}$ into the conservative $\overline{D}_i \leq D_{\max,i}$, so that the problem defined in Sec. III becomes:

$$\begin{aligned} &\max\ \mu_S(P_{S,1}, P_{S,2}, \phi) \\ &s.t. \begin{cases} \frac{1-\lambda_{P,1}}{\mu_{P,1}(P_{S,1},\phi) - \lambda_{P,1}} < D_{\max,1} \\ \frac{1-\lambda_{P,2}}{\mu_{P,2}(P_{S,2},\phi) - \lambda_{P,2}} < D_{\max,2} \\ P_{S,1} < P_{P,1},\ P_{S,2} < P_{P,2} \end{cases}, \end{aligned} \tag{7}$$

where the objective function $\mu_S(P_{S,1}, P_{S,2}, \phi)$ is the maximum stable throughput of the cognitive node S for a particular choice of the characteristic parameters $(P_{S,1}, P_{S,2}, \phi)$. As detailed in [2], the evaluation of the maximum secondary throughput $\mu_S(P_{S,1}, P_{S,2}, \phi)$ can be carried out by exploiting the dominant system $\mathcal{S}$. In fact, under the assumption that the primary queues are stable (which is guaranteed by the QoS constraints (1)), queue $Q_S(t)$ in the original system is stable if and only if it is in the dominant system $\mathcal{S}$ (see [12]). Therefore, the maximum stable throughput $\mu_S(P_{S,1}, P_{S,2}, \phi)$ can be obtained by assuming primary throughput (6), and is given by the sum of the average departure rates $\mu'_{S,1}$ and $\mu'_{S,2}$ on the radio interfaces Ω_1 and Ω_2, respectively, weighted by the respective handover probabilities ϕ and $1 - \phi$:

$$\mu_S(P_{S,1}, P_{S,2}, \phi) = \phi \mu'_{S,1}(P_{S,1}, \phi) + (1-\phi) \mu'_{S,2}(P_{S,2}, \phi), \tag{8}$$

where $\mu'_{S1}(P_{S,1}, \phi)$ can be written as:

$$\begin{aligned} \mu'_{S,1}(P_{S,1}, \phi) &= \left(1 - \frac{\lambda_{P,1}}{\mu_{P,1}(P_{S,1}, \phi)} \right) (1 - P_{fa,1}) \\ &\quad \times \exp\left(-\frac{\beta_{P,1}}{\gamma_{SP,1} P_{S,1}} \right). \end{aligned} \tag{9}$$

In (9), the first term accounts for the probability of an idle slot (i.e., the event $Q_{P,1}(t) = 0$), the second for the probability of correctly detecting the transmission opportunity, and the third is the probability of successful packet reception at the access point R_1. Similarly, $\mu'_{S,2}(P_{S,2}, \phi)$ can be obtained from (9) by substituting the subscript "1" with "2". In [2], a heuristic approach based on the iteration of a Semi Definite Programming (SDP) algorithm is proposed for the solution of the non-convex optimization problem (7).

V. Numerical results

In this section, we present some numerical results in order to get insight into the performance of vertical handover in the considered system. We express the delay constraint $D_{\max,i}$ ($i = 1, 2$) as a function of the delay $D_{ref,i}$ of the baseline case where only the primary node P_i is active on Ω_i (i.e., the cognitive node S is not present): $D_{\max,i} = (1 + \varepsilon_i)D_{ref,i}$. In other words, parameter ε_i measures the maximum allowed fractional increase in the average delay of primary node P_i ($i = 1, 2$) due to the activity of the cognitive node S.

Fig. 2 represents the optimal vertical handover probability ϕ and the maximum stable throughput μ_S of the secondary node S obtained from (7) versus the ratio between the average channel gains on the two interfaces $\gamma_{SP,1}/\gamma_{SP,2}$ for different values of the parameters $\gamma_{P,1} = \gamma_{P,2}$. Other parameters are selected as: $\gamma_{SP,1} = 10$ dB, $\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.3$ [packets/slot], $P_{e,1} = P_{e,2} = 0.09$ and $\epsilon_1 = \epsilon_2 = 0.15$. Optimal powers (not shown) equal the maximum values $P_{S,1} = P_{P,1} = 1$ and $P_{S,2} = P_{P,2} = 1$ for the range of parameters considered in this and in the following example. It is noted that optimization of (7) is performed numerically by using standard tools for global optimization (but see [2] for a heuristic reduced-complexity approach that is near-optimal). The figure shows that vertical handover with optimized parameters as per (7) allows the secondary to adapt to given network topologies. For instance, it can be noticed that the secondary node tends to privilege sensing on the first radio interface Ω_1 ($0.5 < \phi < 1$) when channel $\gamma_{SP,2}$ is worse than channel $\gamma_{SP,1}$, while it tends to privilege sensing on the second interface Ω_2 ($0 < \phi < 0.5$) when viceversa. Furthermore, as expected, fig. 2-(a) shows that optimal ϕ is equal to 0.5 when $\gamma_{SP,1} = \gamma_{SP,2}$. This means that each the two radio interfaces can be chosen by the secondary node S with the same probability when there is perfect system symmetry. As a reference, the maximum stable throughput achievable by the secondary node when the latter is forced to transmit for all the time only either on the radio interface Ω_1 ($\phi = 1$) or Ω_2 ($\phi = 0$) is also plotted in fig. 2-(b) for the case $\gamma_{SP,1} = \gamma_{SP,2} = 7$ dB. Notice that in this case we assume that the secondary only optimizes its transmission power $P_{S,1}$ if $\phi = 1$ or its transmission power $P_{S,2}$ if $\phi = 0$ in order to maximize its maximum stable throughput under primary QoS constraints according to (7). As it can be seen, the mechanism of optimizing the vertical handover policy allows the secondary node to achieve better performance in terms of maximum stable throughput with respect to strategies in which the only power allocation is optimally managed.

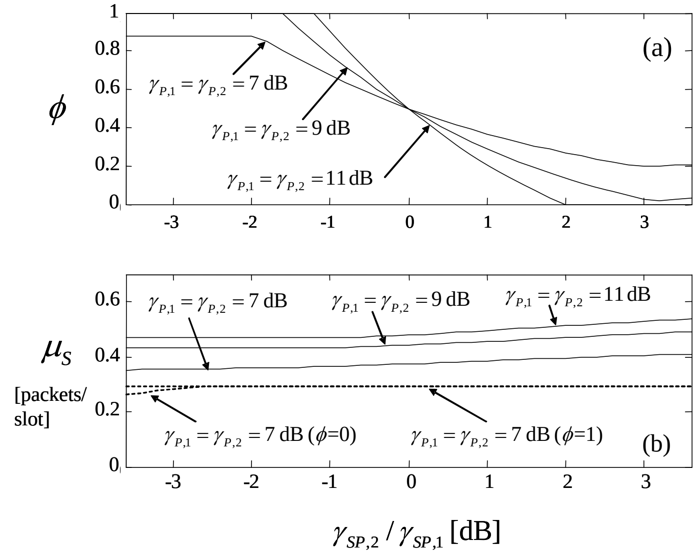

Fig. 2. Optimal vertical handover probability ϕ and maximum stable throughput μ_S of the secondary node S obtained from (7) versus the ratio between the average channel gains on the two interfaces $\gamma_{SP,1}/\gamma_{SP,2}$ for different values of the parameters $\gamma_{P,1} = \gamma_{P,2}$. In fig. 2-(b), the maximum stable throughput achievable by the secondary user through the employment of static access technique is also shown. Other parameters are selected as: $\gamma_{SP,1} = 10$ dB, $\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.3$ [packets/slot], $P_{e,1} = P_{e,2} = 0.09$ and $\epsilon_1 = \epsilon_2 = 0.15$.

Fig. 3 represents the optimal vertical handover probability ϕ and the maximum stable throughput μ_S of the secondary node S obtained from (7) versus the maximum delay constraint on the first radio interface Ω_1, ε_1, for different values of the probabilities of missed detection $P_{e,1} = P_{e,2}$. Other parameters are selected as: $\gamma_{SP,1} = \gamma_{SP,2} = 8$ dB, $\gamma_{P,1} = \gamma_{P,2} = 7$ dB, $\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.35$ [packets/slot] and $\epsilon_2 = 0.15$. The figure shows that the optimal vertical handover mechanism is able to keep the maximum stable throughput achievable by the secondary node S at a constant level even in the presence of very strict delay constraints ε_1 on the first radio interface Ω_1. Similarly to the previous example, in fig. 3-(b), the secondary maximum stable throughput obtained when the cognitive node S employs static access policies ($\phi = 0$ or $\phi = 1$) is shown in order to underline once again the advantages arising from the optimal vertical handover technique.

In order to get further insight into the performance of the system, fig. 4 shows the remarkable advantages in terms of percentage gain in the secondary maximum stable throughput arising from the use of the optimal vertical handover policy with respect to static techniques in which only one interface (here Ω_2) is employed by the secondary for transmission (i.e., by setting $\phi = 0$ in (7), as explained above). Other system parameters are selected as: $\gamma_{P,1} = 8$ dB,

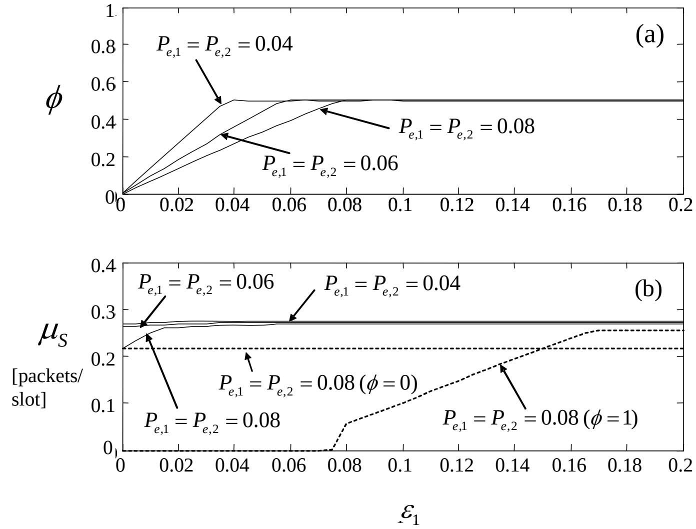

Fig. 3. Optimal vertical handover probability ϕ and maximum stable throughput μ_S of the secondary node S obtained from (7) versus the maximum delay constraint on the first radio interface Ω_1, ε_1, for different values of the probabilities of missed detection $P_{e,1} = P_{e,2}$. In fig. 3-(b), the maximum stable throughput achievable by the secondary user through the employment of static access technique is also shown. Other parameters are selected as: $\gamma_{SP,1} = \gamma_{SP,2} = 8$ dB, $\gamma_{P,1} = \gamma_{P,2} = 7$ dB, $\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.35$ [packets/slot] and $\epsilon_2 = 0.15$.

$\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.3$ [packets/slot], $P_{e,1} = P_{e,2} = 0.09$ and $\epsilon_1 = \epsilon_2 = 0.15$. The figure suggests that the extent of the gain strictly depends on the network topology of the cognitive framework and, in particular, it is larger when the asymmetry between the two radio interfaces is less pronounced. For example, for the selected parameters, we have obtained percentage gains around 100% for very slight differences between channels $\gamma_{P,1}$ and $\gamma_{P,2}$ and, however, percentage gains always larger than 40% can be achieved in the interval $\gamma_{P,1} \leq \gamma_{P,2} \leq \gamma_{P,1} + 0.6$ dB, while they tend to become of the order of 10% when the channel gains $\gamma_{P,1}$ and $\gamma_{P,2}$ differ by 1.5 dB.

VI. Conclusions

In this paper, we have presented a simple cognitive framework composed of two independent primary licensed communication links coexisting with a secondary unlicensed node with the capability of performing a packet-by-packet vertical handover to access the radio resources. The maximum stable throughput of the secondary node under constraints of maximum-delay QoS requirements for the primary transmissions has been investigated by accounting for network topology and measurement conditions. Numerical results have shown that optimal vertical handover has proved an effective technique for enhancing the throughput of cognitive radios while guaranteeing QoS constraints with respect to static access solutions, since more able to adapt to the different network operating conditions. Specifically, the employment of the investigated technique has appeared

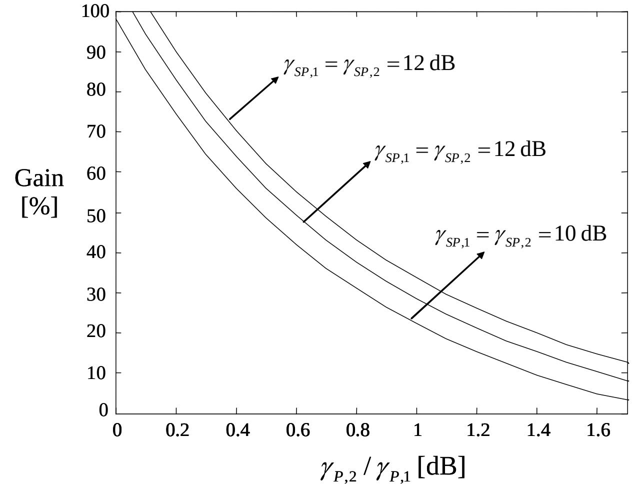

Fig. 4. Percentage gain in terms of maximum stable throughput arising from the optimal vertical handover with respect to a static policy with $\phi = 0$ (only the radio interface Ω_2 is used for all the time) versus the ratio between the channel gains $\gamma_{P,2}/\gamma_{P,1}$ for different values of the parameters $\gamma_{SP,1} = \gamma_{SP,2}$. Other system parameters: $\gamma_{P,1} = 8$ dB, $\beta_{P,1} = \beta_{P,2} = 4$ dB, $P_{fa,1} = P_{fa,2} = 0.01$, $P_{P,1} = P_{P,2} = 1$, $\lambda_{P,1} = \lambda_{P,2} = 0.3$ [packets/slot], $P_{e,1} = P_{e,2} = 0.09$ and $\epsilon_1 = \epsilon_2 = 0.15$.

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