An Opportunistic Access Scheme Through Distributed Interference Control for MIMO Cognitive Nodes

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Abstract—A critical issue of a Cognitive Radio Network is the interference generated by secondary users simultaneously accessing and transmitting over the primary user spectrum band. In this paper, we introduce and study a distributed and opportunistic access scheme for MIMO ad-hoc cognitive radio networks identified as OPTIM-COG (OPporTunistic Interference control for Mimo COGnitive radio). OPTIM-COG is based on simple power stimuli issued by PU transmitters. These stimuli are basic control messages exchanged, at a known power, by both primary transmitter and primary intended receiver for their internal power control. A periodic repetition of this power stimulus and the power control generated in the primary network are used by secondary nodes to get their transmission opportunities. These opportunities are determined with a twofold goal: on the one hand the secondary node will transmit to its secondary receiver only if the quality of the already established primary connection does not decrease below a minimum level, on the other hand the resulting opportunistic access exploits the MIMO performance improvements. We describe the fully distributed version of this access scheme and we theoretically demonstrate, via a game theoretical formulation, that the resulting power allocation is the unique Nash Equilibrium. Performance results present secondary user access maps in the 2D plan, where both MIMO benefits as well as the presence of multiple active secondary links can be represented. Both the cases of a perfect interference measurement and imperfect channel estimation are evaluated.

Index Terms—Cognitive radio, power control, game theory, MIMO.

I. INTRODUCTION

In Cognitive Radio (CR) networks some spectrum portions are dynamically occupied by transmissions of Secondary Users (SUs) coexisting with licensed Primary Users (PUs) [1][2]. Secondary users identify unused or less used portions of licensed spectrum bands and utilize that bands without adverse impact on PU. The resulting radio access is an opportunistic one where SUs exploit spectrum portions without causing harmful interference to PU operating on these bands.

In this paper a distributed access protocol, named OPTIM-COG (OPporTunistic Interference control for Mimo COGnitivie radio), is proposed. OPTIM-COG is an opportunistic access scheme of a set of secondary links accessing to one primary channel. By capturing simple power control messages that are exchanged in the primary network, secondary users are able to estimate the interference that their access would generate in the primary network and select their transmission parameters to access the spectrum in an optimum way (i.e., an optimum power allocation coinciding with the Nash Equilibrium in a game theoretic framework).

We adopt the physical model, a.k.a. Signal-to-Noise-plus-Interference (SINR) model [3],[4], where a transmission is successful if and only if SINR at the intended receiver exceeds a given threshold so that the transmitted signal can be decoded with an acceptable bit error probability. In this model the term opportunistic means that SUs do not search for completely unused spectrum bandwidths, on the contrary they are allowed to transmit if the interference created to the PU is small. This is still an opportunistic way, since SUs transmit when they have the opportunity to not disturb the PUs. This opportunistic access opportunities depend on positions of SU transmitter and receiver, on the powers used in the system by both PU and SU.

Moreover, we address the case of one PU transmitter and its receiver equipped with multiple antennas, and N pairs of secondary nodes also able to stress the spatial dimension via a Multiple-Input Multiple-Output (MIMO). The possibility to include the MIMO behavior on one side is shown to bring benefits in the access of secondary users and on the other side to be quite simple to be implemented even in a noncooperative protocol as the one proposed here. By running the protocol for SU pairs changing their positions in a 2D plan, we are able to derive an access map which provides an overview of the spatial distribution of the transmission opportunities. In this 2D plan the capability of OPTIM-COG to capture all the access opportunities is shown as well as the advantages deriving by the MIMO paradigm.

The main features of OPTIM-COG follow:

1) it is an access strategy for secondary nodes operating under the general physical interference model [3][4]; this means that secondary nodes may access the system only if the resulting SINR at the primary users remains sufficiently high;

2) it is fully distributed and can be used in a cognitive radio ad hoc network;

3) it leverages simple power controlled stimuli that are exchanged in the network;
4) the access scheme computational cost is of the order of a matrix inversion;
5) it is adaptive to varying channels and topological conditions, i.e., fading channels and secondary nodes entering and leaving the network as well as changing the positions;
6) it leverages the advantages of the MIMO transmission at both the PU and SU sides.

Besides, we demonstrate that, in a game-theoretic framework, OPTIM-COG is a competitive optimum for resource allocation since it achieves the, unique, Nash Equilibrium.

The rest of the paper is organized as follows. Section II discusses some related works and presents the main innovative aspects of this paper. Section III describes the adopted model, while the definition of our scheme is proposed in Section IV. Section V gives some game theory results and essentials. In Section VI both a performance analysis and a spatial opportunity detection through access maps are presented. Finally, we conclude the paper in Section VII.

II. RELATED WORK AND PAPER CONTRIBUTIONS

Power control in CR networks has been proposed in many recent works [5][6]. In general optimal solutions for distributed power control have been proposed several years ago (e.g., in the seminal work of Grandhi, Zander, and Yates [7]). Recently, the adoption of these approaches in a cognitive radio systems has been recommended [8]. The distributed power control scheme proposed in [5] is a special case of the standard iterative algorithms aiming at deriving the optimal powers of the secondary users. However, to enforce the Quality of Service (QoS) requirement of the primary users, a centralized control entity is needed.

The work in [6] formulates a power control problem to maximize the network utility of a CR system while constraining the interference to the PU system. Different optimization problems are formulated and solved with the objective of deriving the transmission powers to be used in the cognitive system. The proposed problems are solved via a sequential geometric programming method, that, in some iterations, finds out the optimal powers to be used on the CR and PU links of a network. The optimization is executed at a centralized processor which acquires the necessary channel statistics. The uncertainty of the CR-to-CR channel case is also considered.

The work in [9] proposes a mixed distributed/centralized control scheme that requires the exchange of simple control signaling between cognitive base stations and PUs to perform a power updating process and be able to maximize the throughput of both downlink and uplink of the CR network. Also the work in [10] plays with simple messages exchanged by the primary nodes so as to adapt and control SU powers to maximize the total utility of all SU pairs while satisfying PU outage requirements.

Differently from these works we use the power control performed in the PU system as a mechanism to acquire, in a distributed way, the channels characteristics, and determine the opportunistic access of secondary users in a fully distributed way. We do not assume that the set of CRs allowed to transmit at the same time is already determined and we do not use a centralized entity controlling the QoS at the PU. On the contrary, we propose a protocol based on simple controlling messages exchanged in the PU (like the classical Request to Send - RTS and Clear To Send - CTS) to determine if the access of the secondary users can be done and which is the resulting power.

The idea of using the primary power control is not completely new since it has been adopted in [11] where, in a SISO scheme, it has been used by secondary nodes by assuming perfect channel knowledge both at transmit and receive side of all users. By fact, the assumption of considering no power control for PU as done by several papers, that do not consider the natural dynamic channel variations, represents a simplification. In fact, considering the power of primary user as a fixed parameter leads to an unrealistic solution. On the contrary, modeling its natural behavior (as for LTE or WiMAX) makes the scenario challenging and more close to what is implemented in real systems.

On the basis of the axiomatic framework defined in [8] for cognitive radio we pursue the following four goals:

1) autonomous operation by individual users (PUs and SUs);
2) opportunistic access of the secondary users;
3) interference protection of the primary users;
4) eligibility of the secondary users.

As for point 1), differently from other works, we do not assume a cooperation of PU and SU. This means that SU and PU are autonomous in their operation and this is reflected in the fact that: i) there is not explicit signaling by the PU to the SU; ii) SUs do not cooperate to decide the access to the shared spectrum band. Notice that in other works a central controller (e.g., a local spectrum server in [12]) or the PU itself sends explicit signals to the SUs, if for instance the estimated interference power exceeds the PU limit. On the contrary, in our scheme, primary nodes operate without considering the presence of the secondary nodes. The PU only operates its native power control and on the basis of this control we perform the SU access and power decisions. The absence of cooperation is true also for the SUs, while in fact it has been demonstrated that cooperative games based on the power control can assure an optimal power allocation and efficiency [13], more complicate is the achievement of a competitive optimality under noncooperation, as in our case. In general competition leads to cheaper solutions even if cooperation allows the achievement of an optimum at the expense of, sometimes heavy, signaling.

We propose a scheme that can be adopted also in a MIMO system where both PU and SU are equipped with multiple-antennas. The joint effect of MIMO and Cognitive Radio was investigated in some papers so to maximize the efficiency in the access procedure [14][15]. The work in [14], through antenna selection procedures tries to opportunistically reduce the interference due to primary users. The power efficiency is the goal of the work in [15] that stress the spatial dimension in order to minimize the power consumption under a constrained on the minimum throughput. Furthermore, in [16] an analysis of how MIMO can improve performance is carried out even
if with the goal of maximization of the sum rate and without specifying how to manage the side information.

Another key aspect of our proposal is that we do not suppose to know a-priori wireless channels between interested nodes. Several works assume that these channels are known [17][18]. To perform an optimal power control the paper in [17] assumes that the CR transmitter has perfect channel state information (CSI) on the channels from it to both the PU and SU receivers. Also [18] assumes that channel matrices are perfectly known at both SU and PU receivers. On the contrary, in our case we only assume channel reciprocity while all the channel characteristics are indirectly measured by “overhearing” power control messages and our access scheme is shown to be robust even in the case of a unperfect channel estimation (thus meaning that the performance does not quickly fall when estimation and real channel differs substantially).

We initially defined our proposal in [19] where a simple procedure for only two links (one PU and one SU) was analyzed. The basic idea was that simple messages, identified as Secondary Links (SL) with one Primary Link (PL) were analyzed. The basic idea was that simple messages, identified with one Primary Link (PL) was analyzed. The basic idea was that simple messages, identified by “overhearing” power control messages and our access scheme is shown to be robust even in the case of an unperfect channel estimation (thus meaning that the performance does not quickly fall when estimation and real channel differs substantially).

We extend here the proposal by adding the possibility to support multiple secondary links. To this aim we describe the complete access scheme and the relevant control messages and derive the analysis in this multi-users case. Moreover, in [19] the algorithm able to provide a stable power assignment was based on an iterative computation and limited only to SUs, here we provide a generalized and faster solution based on a system equations and we provide a game theoretic formulation to demonstrate its validity.

### III. COGNITIVE RADIO NETWORK MODEL AND ASSUMPTIONS

We consider a CR ad hoc network deployed in a given area $A$, where $N$ transmitter-receiver pairs of secondary users, also denoted in the following as Secondary Links (SL), coexist with one Primary Link (PL) having licensed access to a given spectrum portion (sub-channel as in OFDMA) of bandwidth $B$. Like in [18][20][21] we have then a system model with $N$ secondary users and one primary transmitter (PT) - primary receiver (PR) on the same spectrum band. However, the proposed approach can be also used when the spectrum band is used by one primary transmitter (operating in broadcast way) toward multiple primary receivers as it is shown in Section VI. The objective is to enable the opportunistic use of this spectrum band by cognitive users coexisting with the primary user.

We assume that:
1) primary nodes operate without being aware of the presence of the secondary nodes;
2) primary nodes do not send specific control signaling to the SUs;
3) the system operates with a framed multi-access scheme;
4) wireless channels between the network nodes are not a priori known and dynamically change over time frames; channel reciprocity holds;
5) both SUs and PUs are equipped with multiple antennas according to the MIMO paradigm;
6) no power allocation is performed among antennas;
7) SUs transmit in an ad-hoc fashion without knowledge of their reciprocal positions and of the PU position;
8) SUs can sense while transmitting.

It is worth noting that assumptions 1) and 2) are typical of a cognitive radio system where PU should not know of the presence of SUs nor communicate directly with them. As for 4), 6), 7) and 8) these are challenging assumptions that only partially have been considered in the past literature, especially all together. Finally, assumption 9) is derived by the classical Carrier Sensing Multiple Access/Collision Detection and/or Avoidance schemes and has been adopted also in other proposals for cognitive systems [12][22][23].

We denote as:
- $T_0$ and $R_0$ the primary transmitter and receiver, respectively;
- $T_i$ and $R_i$ the transmitter and receiver of the $i^{th}$ secondary link, with $1 \leq i \leq N$;
- $P_{i}^{\text{max}}$ and $P_{R_i}^{\text{max}}$ the maximum transmission power of the PT and PR, respectively;
- $P_{T_i}$ the transmission power of the PT after power control;
- $P_{T_i}^{\text{max}}$ the maximum transmission power of secondary transmitter $i$, with $1 \leq i \leq N$;
- $P_{R_i}$ the transmission power of secondary transmitter $i$ after power control, with $1 \leq i \leq N$;
- $P_{i}^{\text{max}}$ the power related to the primary signalling received at the $R_i$ secondary receiver, with $1 \leq i \leq N$;
- $h_{T_i,R_j}(k,j)$ the channel gain between the $k^{th}$ transmit antenna of $T_i$ and the $j^{th}$ receive antenna of $R_i$, with $0 \leq i \leq N$;
- $\gamma_{R_i}$ the SINR on the $i^{th}$ link, with $0 \leq i \leq N$;
- $\gamma_{R_i,\text{min}}$ the SINR threshold so that the transmitted signal can be decoded with an acceptable bit error probability at receiver $R_i$, with $0 \leq i \leq N$;
- $n_T$ and $n_R$ the number of transmitting and receiving antennas, respectively.

Mathematically, the PU and SU link model can be described by the following relationship

$$y(n) = \mathbf{Hx}(n) + \mathbf{w}(n)$$

where $y(n)$ is the column vector representing the sample (at time $n$) received on the antennas, $\mathbf{H}$ models the channel from the $k^{th}$ transmit to the $j^{th}$ receive antenna whose generic element $h(k,j) = l^{-\alpha/2}g_{k,j}$ being $l$ the distance between transmitter and receiver and $g_{k,j}$ the coefficient modeling the behavior of fading between antenna $k$ and $j$. The $\mathbf{x}(n)$ vector gathers the samples transmitted at $n^{th}$ time by the transmitting antennas, while $\mathbf{w}(n)$ models the disturbing signal at receive side (e.g., noise plus interference). Under the physical model [4] a transmission from $T_i$ ($0 \leq i \leq N$) is successfully received by $R_i$, if and only if the SINR at the intended receiver $R_i$ exceeds a reference (minimum) value $\gamma_{R_i,\text{min}}$, so that the transmitted signal can be decoded with an acceptable bit error probability. As envisaged by this model, each SU $i$ ($i = 1, 2, \ldots, N$) can opportunistically exploit the licensed
spectrum band $B$ only if the PU SINR limit is preserved. Once $m$ out of $N$ SLCs are simultaneously active, the SINR for the $i^{th}$ receiver is:

$$\gamma_{R_i} = \frac{P_{T_i} \cdot (T_{T_i-R_i})}{N_0 \cdot B + I(T_m, R_i)}$$

(2)

where

$$I(T_m, R_i) = \sum_{j=0, j\neq i}^{m} P_{T_j} \cdot (T_{T_j-R_i}) \quad \text{with} \quad 0 \leq i \leq m$$

(3)

and $T_{T_i-R_i}$ includes the effects of the whole channel between $T_i$ and $R_i$ under the implicit assumption of collecting the signal coming from transmitting antennas and summing them. It is defined as $T_{T_i-R_i} = \text{Tr}\{H H^H\}_{T_i-R_i}$ with $\text{Tr}$ indicating the trace operator, and $^\dagger$ the conjugation and transposition operator (see [24]). As for the $T_j-R_i$ link, $T_{T_j-R_i} = \text{Tr}\{H H^H\}_{T_j-R_i}$ indicates the interference effect of $T_j$ on $R_i$ and $N_0 = F \cdot K \cdot T$ ($F$ is the noise figure, $K$ is the Boltzmann constant and $T$ is the temperature in Kelvin degrees).

We assume that the primary transmitter $T_0$ uses a super-frame of $\theta_j$ duration to transmit its data to $R_0$ (as happens in several cellular systems like LTE or WiMAX [25]) and $P_{T_0}^{\text{max}}$ is the power used by $T_0$ and $R_0$ to exchange at the beginning of a superframe signaling messages used for the power control since the channel coefficients may change and a new power setting is needed, so the channel is (moderately slowly) time variant [26]. The $P_{T_0}^{\text{max}}$ value is assumed to be known by secondary users, also.

IV. OPTIM-COG DESCRIPTION

The OPTIM-COG protocol operates in different phases as reported in Figure 1 where the interactions between the primary transmitter and receiver and a single $SLC$ are reported. This figure emphasizes that each signal, in principle, can be heard by the secondary nodes. Control messages are exchanged in the PU network on a superframe basis. Without loss of generality, we start by considering a network where all nodes are silenced and a primary transmitter wants to send data to its intended receiver. A qualitative representation of the resulting power profiles is reported in Fig. 2.

1) Primary link set-up: In order to start a transmission the PT transmits at full power a PRY-Request-To-Send (RTS) and can be used by its PU receiver for channel estimation purposes\(^1\) as detailed in Fig. 1 and in the first time period (named slot in the following) of the first figure in Fig. 2. The reference primary receiver then replies with a Clear-To-Send message (PRY-CTS) at full power that includes the power control information so as to allow the minimum required link quality as detailed in Fig. 2 in the second slot of the first figure. So the primary transmitter can adapt its power (in Fig. 2 in the third slot of first subfigure) and proceed with the transmission. This Power Control Sequence (PCS) constituted by PRY-CTS, PRY-RTS and PRY-CTRL, is repeated at the beginning of each superframe. Let us analytically describe this very simple first phase by resorting to the considered metric that is the SINR. The maximum SINR for the $\mathcal{P(L)} (T_0 - R_0)$ is obtained when the transmission is at full power ($P_{T_0}^{\text{max}}$) during the PRY-RTS transmission, that is

$$\gamma_{R_0,\text{max}} = \frac{P_{T_0}^{\text{max}} \cdot T_{T_0-R_0}}{N_0 \cdot B}$$

(4)

so, during the PRY-CTS transmission, the signal detected by PT is so that

$$\gamma_{T_0,\text{max}} = \frac{P_{R_0}^{\text{max}} \cdot T_{R_0-T_0}}{N_0 \cdot B} = \frac{P_{R_0}^{\text{max}} \cdot T_{T_0-R_0}}{N_0 \cdot B}$$

(5)

under the quite realistic hypothesis of reciprocal channel. This is used for power control since, through the PRY-CTS, the PT is able to evaluate the effect of the channel. Finally, when the transmission starts, PT sends its data at a controlled power allowing to achieve the minimum SINR $\gamma_{R_0,\text{min}}$ that is

$$P_{T_0} = \gamma_{R_0,\text{min}} \cdot \frac{N_0 \cdot B}{T_{T_0-R_0}}$$

(6)

2) First secondary access control and link set-up: We consider now the first SLC ($T_1 - R_1$) willing to access the network. We evaluate whether the transmission of $T_1$ disrupts the correct reception of $R_0$. To preserve the primary link, since in our model a transmission from $T_i$ ($i \neq 0$) is treated as interference at the $R_0$ side, $T_1$ needs to evaluate if after its entrance $\gamma_{R_0} \geq \gamma_{R_0,\text{min}}$. This can be accomplished only by estimating (sensing) the link parameters of the primary connection. During the PRY-RTS (first power stimulus of the PT) $R_1$ is able to measure the channel between $T_0$ and itself. This measuring is operated by $R_1$ in the first part of Fig.2 (see the text box “sensing starts here”). So, this measures at its receive antenna $j$ the primary transmitter power (corresponding to $P_{T_0}^{\text{max}}$/nt transmitted by each of the transmit antennas) referred to as $P_{R_1}^{\text{max}} (j)$, by using the following relationship:

$$P_{R_1}^{\text{max}} (j) = \frac{P_{R_0}^{\text{max}}}{nt} \sum_{k=1}^{nt} |h(k, j)|^2 T_{T_0-R_1}$$

(7)

\(^1\)For sake of brevity we do not describe the channel estimation procedure. Since flat fading has been assumed the estimation of a single channel coefficient has been performed according to Minimum Mean Square Error (MMSE) whose application and theoretical justification may be largely explained, i.e., in [27],[28].
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Fig. 2. Qualitative protocol description: power stimuli exchanged in the network and resulting power profiles.

so the power collected though summation by the $n_R$ antennas can be written as

$$P_{R_1,j}^{max} = \frac{P_{T_0}^{max}}{n_T} \cdot \sum_{k=1}^{n_R} \sum_{j=1}^{n_T} |h(k,j)|^2 T_{0-R_1}$$

(8)

and by expliciting the double summation it is possible to see that it coincides with $\text{Tr}(\mathbf{HH}^\dagger)_{T_0-R_1}$, so avoiding the necessity to estimate the channel path-by-path. No power allocation among antennas is operated and this leads to a sub-optimal (on a user basis) power allocation even if it simplifies the transmission side since more simple modulation formats can be used. As representative example, a simple case of $(2 \times 2)$ matrix can be given. The trace of the matrix $\mathbf{HH}^\dagger$ is the sum of the diagonal elements. These are $|h_{11}|^2 + |h_{12}|^2$ and $|h_{21}|^2 + |h_{22}|^2$ so the sum of these two elements can be rewritten as $\sum_{j=1}^{2} \sum_{k=1}^{2} |h(k,j)|^2$ that is equivalent to (8) when $n_R = n_T = 2$. In the same way, $R_0$ is able to evaluate the channel with primary transmitter by measuring the power at receiving antennas as

$$P_{R_0,j}^{max} = \frac{P_{T_0}^{max}}{n_T} \cdot \sum_{k=1}^{n_T} |h(k,j)|^2 T_{0-R_0}.$$  

(9)

Moreover, by comparing the difference between the PT power level at full power and the controlled one (PRY-CTRL), the secondary receiver can evaluate $\mathcal{T}_{T_0-R_0}$. The last parameter to be acquired is $\mathcal{T}_{T_1-R_1}$, and, thanks to the assumption of channel reciprocal, it is possible to argue that $\mathcal{T}_{T_1-R_0} \equiv \mathcal{T}_{R_0-T_1}$, hence it can be evaluated by considering the power received during the PRY-CTS (see Fig. 1).

As for the secondary link setup, at first $T_1$ sends a RTS to $R_1$, named SRY-RTS, and the secondary receiver uses this message to evaluate the channel $\mathcal{T}_{T_1-R_1}$ and the same does $T_1$ when $R_1$ sends back a CTS, named SRY-CTS (as qualitatively represented in the second sub-figure of Fig. 2). This phase is operated as soon as the primary transmitter ends its PCS (see Fig.2). The choice of starting just after the PCS is due to the sensing operated at the previous frame. The secondary receiver does not recognize other control sequences from secondary users so the control sequence starts just after PCS. It is important to underline that this RTS-CTS exchange is immersed in the interference caused by the primary transmitter. Since the interference level has been already estimated, the received power component is simply the difference between the received one and the already known level, that is

$$\mathcal{T}_{T_1-R_1} = \frac{P_{\text{rec}}(\text{rec}) - P_{T_0} \mathcal{T}_{T_0-R_0}}{P_{T_1}^{max}}$$

(10)

At this stage, $T_1$ knows all parameters to evaluate if the access is possible. In the positive case of access possible, it sends a message named SRY-OP (Opportunistic) at a power level that is the one required to achieve $\gamma_{R_1, min}$ when no interference is present. The usefulness of this message will be explained later. The secondary link is established if and only if: i) $T_1$ transmission does not disturb $R_0$’s reception (that is the SINR at $R_0$ is above or at least equal to $\gamma_{R_0, min}$); ii) the SINR $\gamma_{R_1}$ achieves at least $\gamma_{R_1, min}$.

In order to compute if the transmission by $T_1$ is feasible, the following two equations, corresponding to the two links, primary and secondary respectively, should be solved with respect to power levels:

$$P_{T_0} \mathcal{T}_{T_0-R_0} = \gamma_{R_0, min} (N_0 B + P_{T_1} \mathcal{T}_{T_1-R_0})$$

(11)
and
\[ P_{T_1} \gamma_{T_1-R_1} = \gamma_{R_1,\min}(N_0 B + P_{T_0} \gamma_{T_0-R_1}). \] (12)

This system equation must be solved only by the secondary transmitter. There are some specific cases that may occur. First, if the solution presents \( P_{T_0} \) higher than the maximum allowed value, the SL cannot be established and the same is for negative values of \( P_{T_0} \) or values exceeding the maximum allowed power for the secondary transmitter. On the other hand, for solutions falling in the range between zero and maximum available power level, the secondary link can be established at \( P_{T_0}^* \) power and, as a consequence, the primary transmitter will react with a power level able to solve (11), that is \( P_{T_0}^* \) and no more “reactions” are needed since the minimum SINRs are achieved.

It is important to stress, at this stage, that in order to solve that system equation, the secondary transmitter should have information about all parameters and both the SINR levels. The acquisition of primary link parameters is operated by opportunistic overhearing the set up messaging of the PU link as described in Section IV-1 and in Fig. 2.

Notice that the signaling by the primary link is periodic (frame time) and that each secondary link is silenced during this phase. When a secondary node wants to send its data it needs to sense the channel for at least one frame and then it starts with secondary link signaling. This phase is performed during the transmission operated by the primary link (and possibly other secondary nodes).

3) Generalization to the case of multiple secondary links: Before moving on the general case, let us analyze how the protocol works when more than one secondary link is established. By resorting to Fig. 2 it is possible to note that if a secondary secondary link is going to be established, during the control sequence of the \( T_1 \) and \( R_2 \) starts its sensing and it recognizes the PCS the control sequence of the \( T_1 \) and \( R_1 \) so the control sequence related to the link \( T_2 \) and \( R_2 \) starts just after the signaling operated, in the new frame, by \( T_2 \) and \( R_2 \). Then, when the first secondary \( T_1 \) and \( R_1 \) clears down the connection (i.e., it ends to send its data and the relevant PCS) the second secondary \( T_2 \) and \( R_2 \) continues its signaling in the same (temporal) position within the frame. A third link \( T_3 \) and \( R_3 \) wants to send its data and since no control sequence is recognized just after the primary PCS (since that place has been left free by \( T_1 \) and \( R_1 \)) in the next frame \( T_3 \) and \( R_3 \) starts its signaling just after PCS. In all this signaling procedure, the primary link adapts the power according to the interference perceived. This is in line with WiMAX and IEEE802.11/g for interference coming by other stations operating on the same frequency. In this case the feedback link is the key for power adjustment. Let us move on on the analytic description of the general case of more than one secondary link trying to access the medium. Under the assumption of one primary link established and \( N-1 \) secondary links already active, we want to analyze the case of a new SL (the \( N \)th) to be established. Similarly to the previous case a system equation should be solved by considering the \( N+1 \) links. In a matrix and vectors shape the general equation is

\[ T_{N+1} \gamma N_{P+1} = N_0 B \gamma N_{T+1}, \] (13)

where the \( (N+1) \times (N+1) \) matrix is given by

\[ T_{N+1} = \begin{bmatrix} \gamma T_{T_0-R_0} & \ldots & -\gamma_{R_0,\min} \gamma T_{T_0-N-R} \\ \ldots & \ldots & \ldots \\ -\gamma_{R_N,\min} \gamma T_{T_N-R_N} & \ldots & \gamma T_{T_N-N-R} \end{bmatrix}, \] (14)

the vector of power levels to be optimized is

\[ p_{N+1} = [P_{T_0} P_{T_1} \ldots P_{T_N}]^T, \] (15)

and the SINRs are given by

\[ \gamma_{N+1} = [\gamma_{R_0,\min} \gamma_{R_1,\min} \ldots \gamma_{R_N,\min}]^T. \] (16)

The solution of the above problem is given by

\[ p_{N+1}^* = [P_{T_0}^* \ldots P_{T_N}^*]^T = N_0 B T_{N+1}^{-1} \gamma. \] (17)

Differently from the simple case of only one SL in the network, this problem involves several nodes in the power allocation procedure. This means that when already active secondary users recognize a new connected user via its signaling, they evaluate the new matrix \( T_{N+1} \). Since each secondary pair can evaluate those parameters this information is “virtually” shared (that is, all the nodes have the same matrix \( T_{N+1} \) and the result of the optimization is the same, so each node will eventually access with power \( P_{T_i} \).

It is important to remark that when the \( N \)th secondary pair wants to access the medium if the \( N \) system equation does not have a solution (it means that the allocated power are out of the range \( [0, P_{\max}] \)), the \( N \)th secondary link is not established. Otherwise, the \( N \)th SL is established without reducing SINRs of already active connections.

There are two classes of parameters for each existing secondary link that should be acquired. The first class regards the channel related to a secondary link \( (T_{T_i-R_i}) \) while the second class involves the interference measures \( (\sum_i I(T_i, R_i)) \). It is not possible to know the channel and the interference since the SINR is a ratio of this two elements (plus the presence of noise). The use of the SRY-OP slot is fundamental in this sense. In fact, the power level of this last is the one that should be used in absence of interference. In this sense, the power used by this kind of signaling by the \( l \)th link is \( P_{T_l}^{OP} \) and this has the property

\[ P_{T_l}^{OP} = \frac{\gamma_{R_l,\min} N_0 B}{T_{T_l-R_l}} \] (18)

so by detecting the power level at the generic \( R_l \) secondary receiver during the SRY-OP and comparing it with the controlled power, it is possible to solve the simple system characterized by two equations and two variables \( (T_{T_l-R_l} \) and \( \sum_i I(T_i, R_i)) \)

\[ T_{T_l-R_l} = \frac{N_0 B \gamma_{R_l}}{P_{T_l}^{OP}} \] (19)

\[ \sum_i I(T_i, R_i) = P_{T_l} T_{T_l-R_l} - N_0 B \] (20)

that leads to acquire information about channel and interference experienced by the \( l \)-th link. At a first glance the sensing
operated by secondary nodes may appear heavy since they should hear the channel continuously. This is in line with Bluetooth, e.g., devices that use sensing for power control or Wi-Fi devices that evaluate the SINR for adapting modulation format. Moreover, about the signaling operated at frame level, both primary and secondary links need to perform it since, despite of coexistence issues, the channel may change and new information must be acquired.

**A. Remarks and discussion on the implementation issues**

After the main steps of the protocol have been described, we remark that what is qualitatively presented in Figure 2 is the global power profile at both the PU and SU, and in both cases the powers are selected to not disturb the existing communications. Notice that the PU transmits its PCS in a separate slot where only PUs are authorized to transmit so it cannot be disturbed by SUs during this period. Moreover, during the PU data communication the power used by an entering SU is indeed if this amount of power is sufficient for its receiver to achieve a given SINR. The optimal power allocation searched by solving the system equation in (17) has the objective to allow SU to access only if the PU is not impacted over its interference limit.

As for the implementation of the proposed protocol some points should be remarked. First of all, during the sensing phase, the new secondary pair is able to acquire the \( T_N \) matrix and in principle can derive the actual power allocation. Once established the new power levels, thanks to the system equation via \( T_{N+1} \) matrix and understood if the access is possible, it starts to transmit. As it appears clear from Fig.2, the place in the timeline for signaling is fixed so a new signaling procedure starts only where no signaling is present. Now, since the sensing by secondary users continues during their transmission, it is reasonable that a secondary receiver recognizes a connected user via its signaling, so the new matrix \( T_{N+1} \) can be evaluated. Since each secondary pair can evaluate those parameters, if this information is shared (that is, all the nodes have the same matrix \( T_{N+1} \)) the result of the optimization is the same, so each node will access with power \( P^*_T \). This scheme simply considers the possibility of a reaction by the nodes to the power levels used by the secondary nodes.

Another point to be fixed is how a new node can estimate the parameters since the signaling coming by different secondary transmitters are immersed in data transmission operated by other secondary transmitters. Also in this case the approach follows that has been shown for the simple case of only one secondary pair described in (10), i.e., by using the SRY-OP.

In the proposed scheme there is not an order for the secondary uses to decide who to probe the channel first as well as there is no coordination among different secondary users. The only time synchronization is with the PU superframe that can be unequivocally detected by the PCRs that are assumed to be sent periodically at the beginning of the frame. In this way the only possible collisions in a super frame can happen when two contemporary SUs send their initial power stimuli (SRY-RTS) once they have captured the full power control sequence of a PU or of another SU (see Figure 2) in the same identical time period. This event has a very low probability, given the time duration of the SRY-RTS with respect to the super-frame. To reduce this collision probability it can be added to the protocol a classical backoff mechanism to prevent simultaneous transmission after having heard a complete power control sequence [29].

**B. Complexity of the proposed scheme**

About the numerical effort required by secondary transmitters to access the medium and/or to allocate power, these must solve the problem depicted in (13) so the computational cost is tied to the number of secondary users already present in the network. Once acquired the parameters through the opportunistic protocol, the heaviest part of the algorithm is represented by the matrix inversion. In fact, the generic secondary receiver that solves the problem has to operate a matrix inversion (of a \( N + 1 \times N + 1 \) matrix) whose maximum cost is of the order of \( O((N + 1)^3) \). Then also the product to the inverted matrix by the SNR vector must be considered and this is of the order of \( O(N + 1) \). So the whole cost is \( O((N + 1)^3) + O(N + 1) \). This problem must be solved at each super-frame since, despite of the number of accessing nodes, leaving the network or joining it, the channel coefficient changes due to the block-fading model. At a first glance the cost may appear high but, in practice, the maximum value of \( N \) is of the order of ten as will be shown in Section VI. So, in order to understand how and how much this complexity reflects on real performance, a simple numerical example lead us to conclude that the cost is sustainable. As from the numerical results the number \( N \) of secondary users that can be connected is limited to a number of the order of 10. This implicitly suggests that with a smartphone equipped with a 1 Ghz processor, the average computation time is of the order of about 1.3 ms that is a value in line with the processing delays required in this kind of system.

Moreover, we remark that the power allocation is solved in a unique iteration, e.g., one superframe, when the entering SU derives the system parameters to solve the system equation in (17). If the result is that the new SU can access, all other active links (primary and secondary) will vary their powers in accordance to what has been pre-computed in (17) in the previous superframe.

**V. Game Theoretic Interpretation of OPTIM-COG**

In order to give an interpretation of the dynamic behavior of the network composed by multiple mutually interfering not cooperating transmit nodes, we resort to the formal tool of the Game Theory [30]. We recall that a noncooperative and strategic game \( \mathcal{G} \) has three components [30]:

\[
\mathcal{G} \triangleq \mathcal{N}, \mathcal{A}, u >\{P, \mathcal{S}, \mathcal{C}\}, \mathcal{P}, \{u\} \tag{21}
\]

that are the set of players (\( \mathcal{N} \)) i.e. the transmit-receive pairs of secondary nodes \( \{(P, \mathcal{S}, \mathcal{C})\} \), the actions \( \mathcal{A} \) that are in the set \( \mathcal{P} \) of the powers that each node allocates and the utility function \( u \) that is the vector gathering the SINRs as defined.
in (2). Thus, after indicating by \( p \in \mathcal{A} \) an action profile, by \( p_i \in \mathcal{Y}_i \) the players action in \( p \) and by \( p_{-i} \) the actions in \( p \) of the other \((m-1)\) players, we can say that \( u_i(p) = u_i(p_i, p_{-i}) \) maps\(^2\) each action profile \( p \) into a real number. In particular, in a strategic noncooperative game each player chooses a suitable action \( p_i^* \) from his action set \( \mathcal{Y}_i \) so to maximize its utility function, according to the following game rule \([30]\):

\[
p_i^* = \max_{p_i \in \mathcal{Y}_i} u_i(p_i, p_{-i}). \tag{22}
\]

Therefore, since there is no cooperation among the players, it is important to ensure the dynamic stability of the overall game. A concept which relates to this issue is the so-called Nash Equilibrium (NE). Simply stated, a Nash Equilibrium is an action profile \( p^* \) at which no player may gain by unilaterally deviating \([30]\). So, a NE is a stable operating point of the Game, because no player has any profit to change his strategy \([30]\). More formally, a NE is an action profile \( p^* \) such that for all \( p_i \in \mathcal{Y}_i \), the following inequality is satisfied \([30]\):

\[
u_i(p_i^*, p_{-i}) \geq u_i(p_i, p_{-i}), \quad \forall i \in \mathcal{N}, \forall p_i \in \mathcal{Y}_i. \tag{23}
\]

In this environment the concept of action-and-reaction is hidden since the equilibrium point, if it exists, is the solution of the system equation (13). In the first example we analyzed, we consider when only one primary and secondary links are present. In that case the choice operated by the secondary node forces the primary to achieve the power level so allowing the achievement of the NE without power adjustments. This is kind of game is a cheating\(^3\) one, in fact, since the secondary pair knows the channel parameter, it can act so to force the primary link to take the action achieving the equilibrium. It is the same of knowing the card of opponent players and, in this sense, the secondary pair is cheating. This, obviously, can be extended to the general case of \(N\) SCIs in the network.

This approach is noncooperative since a not active SCI decides for an access according to the cognitive paradigm of not disturbing existing links without exchanging messages with other nodes, without coordination for deciding what is the best way to access. In fact, in principle, some nodes may consume less power than others already active, so a cooperative approach would grant access to the less consuming. This is out of the cognitive paradigm since, when a node wants to communicate, it can do if the resources (interference) allow it. In order to guarantee the existence of a NE we should introduce the game with a slightly difference with respect to conventional games.

We restrict the game to the players that are playing (at a generic time instant \( t_x \)) and we define the game as

\[
\mathcal{G}^t = \{ \mathcal{N}, \mathcal{A}, \mathbf{u} \} \tag{24}
\]

where \( \mathcal{N} \subseteq \mathcal{N} \) and the number of players are defined according to a preliminary condition to be met, that is, the condition that allows the access without reducing the level of SINR

\[^2\]The notation \( u_i(p_i, p_{-i}) \) emphasizes that the \( i \)-th player controls only own action \( p_i \), but his achieved utility depends also on the actions \( p_{-i} \) taken by all other players \([30]\).

\[^3\]We introduce, for the first time, the concept of cheating game, that is characterized by one or more players knowing the parameters of the others and acting so as to implicitly force to only one single move.

\[^4\]The set \( \mathcal{Y}_i \) is the set describing power levels allowed to the user \( i \).
interference ratio. However, in the case of multiple users, it is possible to find a new power allocation for all the users. This is because the system equation as a finite solution meeting constraints is no more only one but at least two. This is different, for the above assumption, from the NE allowing, at the same time, the achievement of all constraints met. This is different, for the above assumption, from the NE allowing, at the same time, the achievement of all constraints met.

3) This property is very simple to demonstrate. Due to the presence of noise if we consider \( l \)-times the SINR for the user \( i \), then this is larger than that obtained amplifying the signal and the interference \( u_i(lp) \). As interesting result, we have that bringing to infinity the parameter \( l \), this leads to infinity \( l u_i(p) \) while \( u_i(lp) \) is limited by the SIR (Signal to Interference Ratio).

1) Remark about Nash Equilibrium and OPTIM-COG: The Nash Equilibrium, as stated above, is the stationary point of the system, related to the problem defined in (22) from which no players has advantage to move. It is unique in this case as proved. Let us assume that the system equation outputs a different solution with respect to the Nash Equilibrium. In that case the SINRs achieved by the secondary links will be those required by the system and since the system equation is linear and the number of variables is equal to that of equations, it has only one solution. This leads to conclude that there is only one configuration allowing the achievement of SIR coming from OPTIM-COG, that is, a stationary point of the system with all constraints met. This is different, for the above assumption, from the NE allowing, at the same time, the achievement of all constraints. This leads to an absurd since the stationary point meeting constraints is no more only one but at least two. This proves that NE is achieved by OPTIM-COG. Intuitively, let us start from an equilibrium point (it can be with the network totally empty, a trivial Nash Equilibrium, or with some nodes connected). The game is played when something change. This implicitly means that any modification (channel gains due to channel coherence time, nodes leaving, nodes trying to join) induce a new game round. The environment is understood by all the nodes (with the exception of PU that does not compete since it has a different priority) by opportunistically hearing signalling. So, in principle, each node solves the system equation and finds its optimal power level. This not necessarily coincides with the maximum value. If starting from Nash Equilibrium point a new node wants to join, if it is possible (the system equation as a finite solution meeting constraints) a new power allocation is needed for all the users. Otherwise the new node cannot join.

VI. PERFORMANCE ANALYSIS

By using OPTIM-COG we can provide an overview of the spatial distribution of the transmission opportunities for secondary links in the proximity of a primary link. We consider a square area \( A \) where a PT is in the center and its receiver at a given distance (see Fig.3). We divide \( A \) into a \( 40 \times 40 \) grid of \( 5 \text{m} \times 5 \text{m} \) cells (in a number of \( N_{\text{cells}} \)), and locate some secondary links. The \( T_i \) is in each cell and the corresponding \( R_i \) at a maximum distance of one cell. All the simulations were implemented in MATLAB considering the system model parameters reported in Table I.

We consider first the case of one PU and an already active SL (the pair in the right corner of Fig. 3) are present in the network. Although the model in Sect.IV-1 considers only one primary link, we can easily extend the analysis to a multiple case (one PT multiple PRs). In particular the power control will be performed according to the worst case, that is, the primary link exhibiting the lowest signal to noise ratio, so each SU will adapt its behavior by referring to this last. The access possibilities for a new (second) secondary pair have been evaluated in Figs. 4(a), 4(b), 4(c) and 4(d). The red cells represent the zones where the transmission by the secondary transmitter cannot be operated since it can generate too much interference to the primary link. The yellow points represent the cells where the transmission is not disruptive for the primary link but requires too much power to the secondary transmitter. Lastly, the green zones are the cells where the access can be performed without disrupting \( \gamma_{R_{\text{min}}} \). It is to be noticed that, to be close to reality, SUs have a \( P_{\text{Tmax}} \) that is lower than the maximum power of the PU. The three different plots refer to a different antennas configuration that is 1, 2, 4 and 8 respectively. When two links are active (one primary and one secondary) the access by a new secondary pair is really hard as can be recognized from Fig. 4(a) that presents very few green points. Moving to two antennas and after to 4 antennas it is possible to see how the green points increase even if, in this case, the zone between the PT and PR is red while in the case of only one secondary link was yellow. This is due to two interference effects for the second pair given by primary transmitter and first secondary transmitter. Finally, moving to 8 antennas, the green zones become larger so allowing the new secondary pair to opportunistically access. It is important to stress that the proposed opportunistic protocol, is able to work also in the presence of more than one primary node.

In Figs. 5(a), 5(b), 5(c) and 5(d) it is possible to appreciate the effect of channel estimation on the access opportunities.
TABLE I
SYSTEM MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Area</td>
<td>$A$</td>
<td>$200 \times 200$ m$^2$</td>
<td>Noise Figure</td>
<td>$F$</td>
<td>3 dB</td>
</tr>
<tr>
<td>Path Loss Exponent</td>
<td>$\alpha$</td>
<td>2</td>
<td>Primary Max Power</td>
<td>$P_{T0}^\max$</td>
<td>$10^{-3}$ mW</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$B$</td>
<td>$10^6$ Hz</td>
<td>Secondary Max Power</td>
<td>$P_{T1}^\max$</td>
<td>$10^{-5}$ mW</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T$</td>
<td>290$^\circ$ K</td>
<td>Minimum SINR at $R_0$</td>
<td>$\gamma_{R_0,\min}$</td>
<td>15 dB</td>
</tr>
<tr>
<td>Boltzmann Constant</td>
<td>$K$</td>
<td>$1.38 \cdot 10^{-20}$ mW/K · Hz</td>
<td>Minimum SINR at $R_1$</td>
<td>$\gamma_{R_1,\min}$</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

The SINR values considered during the estimation phase are, for the four plots, infinity (perfect estimation), 20dB, 10dB and 3dB while the performance requested during the data transmission phase is the same of the previous examples. From the comparison with the perfect estimation phase, when $n_T = n_R = 4$, it is evident that the red zones (indicating a forbidden transmission/access) become yellow thus meaning that the secondary nodes, erroneously, cannot access due to insufficient available power, so they believe that the possible interference would not be harmful. Even this represents a drawback, this procedure can be still considered robust to estimation errors since the access opportunities (green zones) do not change considerably and possible difference fall in fading fluctuation. This implies that the effect of channel knowledge has an impact where the access by secondary nodes is not possible while it does not affect substantially the access opportunities (the green cells). The estimation error is defined as in [28].

A. Effects of fading on the required power

The effect of fading statistics has been evaluated in Fig. 6 where two different situations are considered (zero mean unit variance). The first case is related to Rayleigh flat fading for both primary and secondary link. What is depicted in Fig.6 is the power spent for achieving the target SINRs by increasing the number of antennas. As expected the power level decreases both for primary transmitter and secondary one. This is essentially due to the scattering that allows, under the assumption of non-correlation among channel (antenna) gains, diversity and coding gain. More interesting is the behavior of the system when the primary link suffered for Rayleigh flat fading while the secondary link present Rice distributed fading. This assumption is not unrealistic since it is reasonable that between secondary nodes a Line Of Sight exists. In this case, the power spent by the secondary node is considerably lower than the previous case of Rayleigh fading. This effect reflects also on the power adopted by the primary
achieving target SINRs. The first one can be justified by observing that increasing the number of antennas does not increase the SINR considerably since the performance are dominated by interference (and not noise) so no power saving is guaranteed. This can be justified by considering that in Rice fading the diversity gain is negligible. The difference between the Rice and Rayleigh case is due to the power saving (and also interference reduction) when a direct path is present.

B. Access probability

The numerical plots in Fig. 7 for Rayleigh flat fading, show the access probability of secondary nodes when 1 secondary pair, 2 or 3 pairs try to access. The access probability is numerically computed by increasing the number of antennas equipping the transmitters and receivers. Formally speaking the access probability is defined and measured as

\[
Pr(\text{access}) = \int_{\gamma^*}^{+\infty} p(\gamma)d\gamma \approx \frac{\sum_{\text{cells}} Pr(\gamma > \gamma^*)}{N_{\text{cells}}}. \tag{28}
\]

More, the values are obtained via a double averaging procedure. The first one is a spatial averaging (over the topological position) while the second one takes care of different channel realization, so a total of 16000 trials have been considered. As it appears evident the access probability for only one secondary pair when a primary transmitter is active is considerably higher than the cases of two and three pairs when each node is equipped with only one antenna. In fact, he probability

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(a) perfect estimation

(b) low estimation error

(c) medium estimation error

(d) high estimation error

Fig. 5. Access maps when one primary link and one secondary link are present $\gamma_{R0, min} = 15$dB, $\gamma_{R1, min} = \gamma_{R2, min} = 10$dB, $n_T = n_R = 4$ and different estimation quality levels

Fig. 6. Power spent for different antenna configurations when Rayleigh and Rice fading have been assumed.
f9s 8.3 of one pair to 0.2 9.05 of two and three pairs respectively. By increasing the number of antennas it is possible to observe how the access probability achieves 0.93 when 8 antennas are considered for only one pair, while this value reaches 0.81 and 0.71 for two and three pairs. It is also interesting to note that the probability does not approach 1 since, as already seen in the access maps, the zones close to the primary receiver (due to interference induced) and transmitter (due to interference suffered) are not accessible. In Table II the effect of the spatial diversity on the average number of accessing users has been considered. The average number of accessing user is measured as the ratio of user accessing \((N_a)\) over the number of users requiring access \((N_r): \frac{A}{N} = \frac{N_a}{N_r}\).

The obtained value is averaged in a spatial sense. So, moving from a single antenna system to a 8-antennas one, the average number of active secondary links ranges from 1.04 to 7.8. It is interesting that, from a numerical point of view, the number of secondary pairs that we can allocate in the network is of the same order of magnitude of the antennas employed in the proposed access protocol. Recall that the complexity of the proposed scheme is in the order of \(O(N^3)\), then in the case of a quite complex MIMO system (8 antennas) the complexity to run the algorithm is around 512.

With regard to the number of accessing users, we consider on the access map access opportunities above the 75% (i.e., where a 5 x 5 cell, after running and averaging the simulations, exhibits a value above 0.75 of access success) and we numerically evaluate the access probability of a \(i^{th}\) secondary pair conditioned to the (already performed) access of the \(P\) and \(i - 1\) \(S\)s on an area basis. Therefore once the 5 x 5 m\(^2\) is sampled, as in the previous maps, we report in Table III, the number of zones where the access opportunities is more than 75% by considering different antenna configurations. By considering the network topology in Fig.3 depicting primary and secondary users, the behavior of access requests and leaving are reported in Fig.8.

The first plot of Fig.8 reports the access request and also the connections cleared down while the second plot reports the behavior of the proposed protocol in terms of access granted. Moreover, here not only the behavior of the sum \(S\) is reported but also the primary link jointly with the network sum rate (sum of rates of the pairs) evaluated by resorting to the well known Shannon-derived formula

\[
R_i = B \log_2 \det[I_{n_T} + \frac{\gamma_i}{n_T} \mathbf{H} \mathbf{H}^H].
\]

The bottom plot reports the behavior of the protocol. By comparing the two plots we notice that the protocol is able to grant access to all \(S\)S except for \(S_1\) since this access is required when PT-PR and \(S_9\) are already connected. This justifies also why the sum rate is lower than that present in the upper plot at time interval 13. By excluding this particular situation, all the other requests are accomplished and this justifies the difference, in terms of sum rate, between the requested access and obtained one. We notice that the fairness depends on the position of the entering secondary links and on the time period they try to enter. Some \(S\)s that are in a position that may cause too much interference to the already present ones and to the \(P\) will not enter the system (e.g. the \(S\) between \(S_9\) in Fig.3 in the figure). This is part of the opportunistic access (not all users have the same opportunities). On the other hand the protocol is fair for all the entered users since they achieve the same minimum SINR \((\gamma_{R, min})\) and the same rate as reported in Figure 8.

Lastly, it is possible to note that the primary rate does
not change during time. The works in [8] and [11] consider SISO access and MIMO sum rate maximization, respectively. By performing simulations and comparison, the OPTIM-COG exhibits the same performance of [8] when no diversity is used (SISO) with the difference of considering real measured channels in place of perfect information. Moreover, even if the goal of this work and [11] are different, allowing the access (constraining) to the same number of the users in our network leads to the same (maximized) sum rate even if, in this case, OPTIM-COG considers real measured channels in place of perfect information.

VII. CONCLUSIONS

In this paper we proposed an access scheme for cognitive secondary nodes. The scheme is opportunistic in nature and is based on the overhearing of simple power control messages exchanged in the network. We considered a network scenario consisting of $N$ pairs of secondary users, having a low priority in the use of the licensed channel, and a pair of primary users. Secondaries try to communicate using the same channel of the PU still assuring the transmission performance requirements both for the primary users and for themselves. We used the notion of power stimulus, a transmission at a known power, for the computation of some important system parameters, such as the channel between secondary users and primary users, that help the SUs in the estimation of the interference caused at the primary receiver. By applying the estimated parameters in the Physical Model, the secondary transmitters are able to decide if the transmission towards its intended secondary receiver can take place without violating the SINR constraints at the primary receiver and the SINR of the already active secondary links. Since the proposed strategy is noncooperative we also provided a game theoretic interpretation of the derived solution. Beside the fact that the proposed approach is fully distributed another key novelty is that is can be applied in a MIMO system. To show the results we provided a spatial characterization of the transmission opportunities including the effect of MIMO: by fixing the position of the primary nodes and moving the secondary ones in a 2D plane, we obtained access maps representing the areas which are most likely to produce high levels of interference. We also tested the effects of different fading channel models in the proposed scheme as well as the effect of an imperfect channel estimation.

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