Resource Allocation for Cognitive Radio Networks with a Beamforming User Selection Strategy

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***Abstract*— In this paper[1] we address the problem of resource allocation in the context of cognitive radio networks (CRN). With the deployment of K antennas at the cognitive base station (CBS), an efficient transmit beamforming technique combined with user selection is proposed to maximize the uplink throughput and satisfy the signal-to-noise and interference ratio (SNIR) constraint, as well as to limit interference to the primary user (PU). In the proposed user selection algorithm, secondary users (SUs) are first pre-selected so as to maximize the per-user sum capacity subject to minimize the mutual interference. Then, the PU verifies the outage probability constraint and a number of SUs are selected from those pre-selected SUs. Simulation results show that our proposed method exhibits a significant number of cognitive users able to transmit while minimizing interference to guarantee QoS for the PU. We also compare the results obtained by the proposed method to those obtained using a binary power allocation method. The reported results demonstrate the efficiency of the proposed technique to maximize the SU rate while maintaining a QoS to a PU, and its superiority to the binary power allocation.**

Keywords—Cognitive Radio, Resource Allocation, Beamforming, User Selection.

I. Introduction

Due to the accelerated deployment of broadband communication systems and current fixed frequency allocation schemes, spectrum is becoming a major bottleneck. However, experiments show that up to 85% of the spectrum remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum scarcity problem [1]. This observation has recently led to the new paradigm of *opportunistic spectrum sharing*, where users can actively seek for unused spectrum in licensed bands and communicate using these spectrum holes. This vision is supported by regulatory bodies, such as the Federal Communications Commission (FCC) [2] and the European Commission (EC) [3]. The concept is also often referred to as Cognitive Radio (CR) [4].

To enable the vision of opportunistic spectrum sharing, many problems remain to be solved. Most importantly, the interference caused by sharing the same radio channel becomes an obstacle that limits system performance, such as the system throughput. Thus, when sharing the spectrum with the primary user (PU), one tries to find a way to increase the throughput [5].

Multiple-input/multiple-output (MIMO) systems have great potential to enhance the capacity in the framework of wireless cellular networks [6] [7]. Multiple antennas can for example be deployed at a cognitive base station (CBS). Many wireless network standards provision the use of transmit antenna arrays. Using baseband beamforming, it is possible to steer energy in the direction of the intended users, whose channels can often be accurately estimated [7] [8]. Beamforming has been also exploited as a strategy that can serve many users at similar throughput. Moreover, beamforming has the advantage of limiting interference. Thus, we are interested in transmit beamforming schemes for cognitive transmission. For this purpose, we utilize joint beamforming that implies an extension to the transmitter side of classical receive beamforming.

In this paper, we address the problem of user selection strategy in the context of a cognitive radio network (CRN). We consider the primary uplink of a single CRN, where cognitive transmitters transmit signals to a number of secondary users (SUs) using adaptive antennas, while the primary BS receives its desired signal from a primary transmitter and interference from all the cognitive transmitters. With the deployment of K antennas at each cognitive transmitter, an efficient transmit beamforming technique combined with user selection is proposed to maximize the sum throughput and satisfy the signal-to-noise-and-interference ratio (SNIR) constraint, thus limiting interference to the primary BS. Using this approach, transmit beamforming weights can be found. In the proposed user selection algorithm, SUs are first pre-selected so as to maximize the per-user sum capacity, subject to minimization of the mutual interference. Then, the PU verifies the outage probability constraint, and a number of SUs are selected from those pre-selected SUs.

The rest of the paper is organized as follows. In Section II we describe the channel model and develop the proposed beamforming strategies. In Section IV, the user selection algorithm is presented. Simulation results and a comparison with a previously published binary power allocation method are provided in Section V, and Section VI concludes the paper.

[1]The work reported herein was partially supported by the European project SENDORA and the national project GRACE.

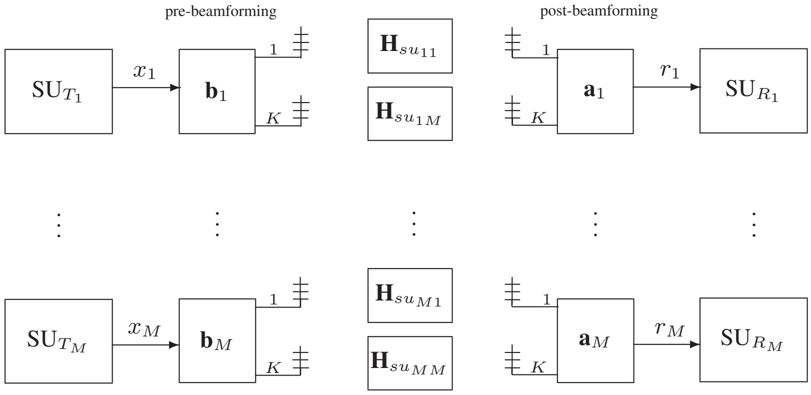

Fig. 1. Multiple transmit and receive secondary users system structure.

II. Channel Model

In this section, we define the channel, which consists of multiple transmit/receive SU links randomly distributed over the geographical area considered. The SU MIMO system is given by Fig. 1. By virtue of a scheduling protocol, one PU and M SU pairs are simultaneously selected to communicate at a given time instant, while others remain silent. In the coverage area of the primary system, there is an interference boundary within which no SUs can communicate in an ad hoc manner.

The SU system structure is based on beamforming at both the transmitter (K antennas) and the receiver (K antennas) for each SU link. The number of secondary transmitters (SU_T) is equal to M, and is equal to the number of secondary receivers (SU_R). Assuming that many scatterers are located around the transmitter and receivers, the channel coefficient matrix $\mathbf{H}_{su_{rt}}$ (the channel between the t-th transmit SU and the r-th receive SU) exhibit flat fading. The channel gain vector $\mathbf{h}_{pu_m}$ from the PU indexed by pu to a desired SU m (m between 1 and M) is given by:

$$\mathbf{h}_{pu_m} = [h_{pu_m,1}...h_{pu_m,K}]^T \tag{1}$$

where the channel gains are assumed i.i.d. random variables. We consider that the channels between different users are independent. We then set the received signal of the m-th user as follows (the index of SUs m lies between 1 and M):

$$\mathbf{y}_m = \mathbf{H}_{su_{mm}}\mathbf{s}_m + \sum_{l=1,l\neq m}^{M} \mathbf{H}_{su_{lm}}\mathbf{s}_l + \mathbf{h}_{pu_m}x_{pu} + \mathbf{n}_m \tag{2}$$

with $\mathbf{n}_m$ of size $K \times 1$ being zero-mean i.i.d. Gaussian noise with power σ_m^2, and K being the number of antennas. $\mathbf{s}_m$ is the transmit vector of size $K \times 1$ for the m-th SU and x_{pu} being the transmit sample sent from PU. $\mathbf{y}_m$ is the receive vector of size $K \times 1$. $\mathbf{H}_{su_{mm}}$ ($K \times K$ matrix) is the channel between the m-th SU_T and the m-th SU_R and $\mathbf{H}_{su_{lm}}(l = 1, ..., m-1, m+1, ..., M)$ are channel matrices between the other SUs, referred to as the *interference channel matrices*.

Here, a joint beamforming approach is proposed for the SU system, that is, all the transmitters and receivers exploit a beamforming architecture [7]. The transmission scheme is characterized by the power allocation (eigenvalues of the transmit covariance matrix) and the orientation (eigenvectors of the transmit covariance matrix) [9]. This yields

$$\mathbf{s}_m = \mathbf{b}_m x_m, \qquad m = 1, ..., M \tag{3}$$

where $\mathbf{b}_m$ is the pre-beamforming vector and x_m is the transmit sample for m between 1 and M. The output of the m-th receiver beamformer is:

$$\begin{aligned} r_m &= \mathbf{a}_m^H \mathbf{y}_m \\ &= \mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m x_m + \mathbf{a}_m^H \sum_{l=1,l\neq m}^{M} \mathbf{H}_{su_{ml}} \mathbf{b}_l x_l \\ &+ \mathbf{a}_m^H \mathbf{h}_{pu_m} x_{pu} + \mathbf{a}_m^H \mathbf{n}_m \end{aligned} \tag{4}$$

where $\mathbf{a}_m$ is the post-beamforming vector at the receive SUs. $\Phi_m = E\{\mathbf{n}_m\mathbf{n}_m^H\}$ is the associated covariance matrix.

The signal-to-noise-and-interference ratio (SNIR) at the m-th SU is:

$$\begin{aligned} \mathrm{SNIR}_m &= \frac{E\{|\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m x_m|^2\}}{E\left\{\sum_{l=1,l\neq m}^{M} |\mathbf{a}_m^H \mathbf{H}_{su_{ml}} \mathbf{b}_l x_l|^2\right\} + E\{|\mathbf{a}_m^H \mathbf{h}_{pu_m} x_{pu}|^2\} + E\{|\mathbf{a}_m^H \mathbf{n}_m|^2\}} \\ &= \frac{|\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m|^2}{|\mathbf{a}_m^H \mathbf{h}_{pu_m}|^2 + \sum_{l=1,l\neq m}^{M} |\mathbf{a}_m^H \mathbf{H}_{su_{ml}} \mathbf{b}_l|^2 + \mathbf{a}_m^H \mathbf{R}_m \mathbf{a}_m} \end{aligned} \tag{5}$$

The per-user sum capacity is:

$$\begin{aligned} \mathrm{C}_{su} &= \sum_{m=1}^{M} \log_2(1 + \mathrm{SNIR}_m) \\ &= \frac{1}{\ln 2} \sum_{m=1}^{M} \ln(1 + \mathrm{SNIR}_m) \end{aligned} \tag{6}$$

and the capacity of PU is:

$$\mathrm{C}_{pu} = \log_2\left(1 + \frac{p_{pu}|h_{pupu}|^2}{\sum_{m=1}^{M} |\mathbf{h}_{pu_m}\mathbf{h}_{pu_m}^H| ||\mathbf{b}_m||^2 + \sigma^2}\right) \tag{7}$$

where h_{pupu} denotes the channel gain between the BS and the PU and σ^2 is the ambient noise variance. The data destined from the primary system is transmitted with power p_{pu}.

III. BEAMFORMING STRATEGY

Here we present the design of the transmit and receive beamvectors. In fact, beamvector associated with each SU is determined by optimizing a certain criterion to reach a specific purpose such as maximizing the throughput or minimizing the interference. To compute the beamvectors, we consider just the SU MIMO system. The reason for this is that the interference among PU is nulled in SNIR equation given in (6). In fact, we propose an algorithm that can minimize the interference between cognitive users. SUs are first pre-selected so as to maximize the per-user sum capacity, and then, the PU verifies the outage probability constraint and a number of SUs are selected from those pre-selected SUs. Specifically, beamvectors are selected such that they satisfy the interference free condition $\mathbf{a}_m^H \mathbf{h}_{pu_m} = 0$. If we consider this condition, the SNIR at the m-th SU can then be written as:

$$\begin{aligned} \text{SNIR}_m &= \frac{E\{|\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m x_m|^2\}}{E\{|\mathbf{a}_m^H \mathbf{n}_m|^2\} + E\left\{ \sum_{l=1, l\neq m}^{M} |\mathbf{a}_m^H \mathbf{H}_{su_{ml}} \mathbf{b}_l x_l|^2 \right\}} \\ &= \frac{|\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m|^2}{\mathbf{a}_m^H \Phi_m \mathbf{a}_m + \sum_{l=1, l\neq m}^{M} |\mathbf{a}_m^H \mathbf{H}_{su_{ml}} \mathbf{b}_l|^2} \\ &= \frac{\left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right)^H \left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right)}{\mathbf{a}_m^H \left(\Phi_m + \sum_{l=1, l\neq m}^{M} \mathbf{H}_{su_{ml}} \mathbf{b}_l \mathbf{b}_l^H \mathbf{H}_{su_{ml}}^H \right) \mathbf{a}_m} \end{aligned} \quad (8)$$

We define the total interference plus noise covariance matrix at the m-th SU as:

$$\mathbf{R}_m = \Phi_m + \sum_{l=1, l\neq m}^{M} \mathbf{H}_{su_{ml}} \mathbf{b}_l \mathbf{b}_l^H \mathbf{H}_{su_{ml}}^H \quad (9)$$

Therefore, the SNIR at the m-th SU can be formulated as follows:

$$\begin{aligned} \text{SNIR}_m &= \frac{\left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right)^H \left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right)}{\mathbf{a}_m^H \mathbf{R}_m \mathbf{a}_m} \\ &= \left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right)^H \left(\mathbf{a}_m^H \mathbf{R}_m \mathbf{a}_m\right)^{-1} \left(\mathbf{a}_m^H \mathbf{H}_{su_{mm}} \mathbf{b}_m\right) \\ &= \mathbf{b}_m^H \mathbf{H}_{su_{mm}} \mathbf{R}_m^{-1} \mathbf{H}_{su_{mm}}^H \mathbf{b}_m \end{aligned} \quad (10)$$

From (10), the post-beamforming vector can be expressed as follows:

$$\mathbf{a}_m = \mathbf{R}_m^{-1} \mathbf{H}_{su_{mm}} \mathbf{b}_m \quad (11)$$

This gives us the following maximization of SNIR at the m-th SU:

$$\begin{aligned} \mathbf{b}_m^H \mathbf{H}_{su_{mm}}^H \mathbf{R}_m^{-1} \mathbf{H}_{su_{mm}} \mathbf{b}_m &\leq \lambda_{max}(m)|\beta(m)|^2 \\ &= \text{SNIR}_m|_{max} \end{aligned} \quad (12)$$

where $\lambda_{max}(m)$ is the maximum eigenvalue of $\mathbf{H}_{su_{mm}}^H \mathbf{R}_m^{-1} \mathbf{H}_{su_{mm}}$ and $|\beta(m)|^2 = \mathbf{b}_m^H \mathbf{b}_m$. For beamforming, the transmitted power through all the SUs for the m-th SU is proportional to $||\mathbf{b}_m||^2$. The design goal is to find the optimum transmit weight vector subject to a carrier power constraint. We consider the power allocation problem corresponding to the distribution of all the available power at the transmitter among all SUs, when the data destined from SU m is transmitted with a maximum power P_{max}. This per-user power constraint is given by:

$$||\mathbf{b}_m||^2 = |\beta(m)|^2 \leq P_{max}, \qquad \forall m = 1, ..., M \quad (13)$$

and the global power constraint is formulated as follows:

$$\sum_{m=1}^{M} ||\mathbf{b}_m||^2 = \sum_{m=1}^{M} |\beta(m)|^2 \leq M P_{max} \quad (14)$$

Concluding that the maximum eigenvalue $\lambda_{max}(m)$ must be chosen so as to maximize the capacity of SUs given a fixed transmit power. In the first step of the proposed beamforming user selection strategy, SUs are first pre-selected so as to maximize the per-user sum capacity given by:

$$\text{C}_{su} = \frac{1}{\ln 2} \sum_{m=1}^{M} \ln\left(1 + \lambda_{max}(m)|\beta(m)|^2\right) \quad (15)$$

If we maximize the per-user sum capacity (C_{su}): i.e. the sum of the SNIR averaged over all SUs under the constraint of maintaining the global power lower than MP_{max}, the problem can be written as:

$$\begin{cases} \text{maximize} & f(\beta(1), ..., \beta(M)) = \text{C}_{su} \\ \text{subject to} & \sum_{m=1}^{M} |\beta(m)|^2 \leq M P_{max} \end{cases} \quad (16)$$

In the second step of the user selection strategy, the PU verifies the outage probability constraint and a number of SUs are selected from those pre-selected SUs. The outage probability can be written as:

$$P_{out} = Prob\left\{\text{C}_{pu} \leq R_{pu}\right\} \leq q \quad (17)$$

where R_{pu} is the PU transmitted data rate and q is the maximum outage probability. The information about the outage failure can be carried out by a band manager that mediates between the primary and secondary users [12], or can be directly fed back from the PU to the secondary transmitters through collaboration and exchange of the CSI between the primary and secondary users as proposed in [13]. To proceed further with the analysis and for the sake of emphasis, we introduce the PU average channel gain estimate G_{pu} based on the following decomposition:

$$h_{pupu} \triangleq G_{pu} * h'_{pupu} \quad (18)$$

where h'_{pupu} is the random component of channel gain and represents the *normalized* channel impulse response tap. This

$$J=\frac{1}{\ln 2}\sum_{i=1}^{M}\ln\left(1+\frac{\lambda_{max}(i)|\beta(i)|^2}{1+\sum\limits_{l=1,l\neq i}^{M}\lambda_{min}^{i}(l)|\beta(l)|^2}\right)-\mu\left(\sum_{i=1}^{M}|\beta(i)|^2-MP_{max}\right)-\nu\left(1-\exp\left[-\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{i=1}^{M}|\beta(i)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)\right]-q\right) \quad (22)$$

$$\frac{\partial J}{\partial\beta(m)} = \frac{1}{\ln 2}\ \frac{2\lambda_{max}(m)\beta(m)}{1+\lambda_{max}(m)|\beta(m)|^2}-2\mu\beta(m)-2\nu\frac{\left(2^{R_{pu}}-1\right)G_{su}^2}{G_{pu}^2p_{pu}}\beta(m)\exp\left[-\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{i=1}^{M}|\beta(i)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)\right]=0 \quad (23)$$

$$g(\beta(i))=\frac{\left(2^{R_{pu}}-1\right)G_{su}^2}{G_{pu}^2p_{pu}}\exp\left[-\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{i=1}^{M}|\beta(i)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)\right] \quad (24)$$

gives us the following PU outage probability expression:

$$\begin{aligned}P_{out} &= Prob\left\{\log_2\left(1+\frac{p_{pu}G_{pu}^2\mid h'_{pupu}\mid^2}{\sum\limits_{m=1}^{M}||\mathbf{b}_m||^2\mid h_{pu_m}\mid^2+\sigma^2}\right)\leq R_{pu}\right\}\\ &\simeq Prob\left\{\frac{p_{pu}G_{pu}^2\mid h'_{pupu}\mid^2}{G_{su}^2\sum\limits_{m=1}^{M}||\mathbf{b}_m||^2+\sigma^2}\leq 2^{R_{pu}}-1\right\}\\ &\simeq Prob\left\{\mid h'_{pupu}\mid^2\leq\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{m=1}^{M}|\beta(m)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)\right\}\end{aligned} \quad (19)$$

From now on we assume for simplicity of analysis that the channel gains are i.i.d rayleigh distributed. However, the results can be immediately translated into results for any other channel model by replacing by the appropriate probability distribution function. Continuing from (19), we have:

$$P_{out}\simeq\int_0^{\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{m=1}^{M}|\beta(m)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)}\exp(-t)dt \quad (20)$$

Finally, we get the following outage constraint:

$$P_{out}\simeq 1-\exp\left[-\left(2^{R_{pu}}-1\right)\left(\frac{G_{su}^2\sum\limits_{m=1}^{M}|\beta(m)|^2+\sigma^2}{G_{pu}^2p_{pu}}\right)\right] \quad (21)$$

To compute the transmitted power through all SUs, we define the Lagrangian expression for this maximization problem as given in (22). We introduce in (22) two variables, μ and ν, called Lagrange multipliers. The solution of all the system is found by calculating the derivatives of J with respect to the power allocation parameters $\beta(m)_{m=1..M}$ and Lagrange multipliers μ and ν.

By calculating the derivatives of J with respect to the power allocation parameters $\beta(m)$, we obtain (23). Using (24) we can express the solution of (23) as:

$$\frac{1}{(\mu+\nu g(\beta(i)))\ln 2}\lambda_{max}(m)=1+\lambda_{max}(m)|\beta(m)|^2 \quad (25)$$

The solution of this problem is formulated as follows:

$$|\beta(m)|^2 = \frac{1}{(\mu+\nu g(\beta(i)))\ln 2}-\frac{1}{\lambda_{max}(m)} \quad (26)$$

The derivatives of J with respect to the power allocation parameters $\beta(i)_{i=1..M}$:

$$\begin{cases}|\beta(1)|^2=\frac{1}{(\mu+\nu g(\beta(i)))\ln 2}-\frac{1}{\lambda_{max}(1)}\\ |\beta(2)|^2=\frac{1}{(\mu+\nu g(\beta(i)))\ln 2}-\frac{1}{\lambda_{max}(2)}\\ \quad .\\ \quad .\\ \quad .\\ \quad .\\ |\beta(M)|^2=\frac{1}{(\mu+\nu g(\beta(i)))\ln 2}-\frac{1}{\lambda_{max}(M)}\end{cases} \quad (27)$$

The sum of all equations in (32) gives:

$$\begin{aligned}\sum_{i=1}^{M}|\beta(i)|^2 &= \frac{M}{(\mu+\nu g(\beta(i)))\ln 2}-\sum_{i=1}^{M}\frac{1}{\lambda_{max}(i)}\\ &= M\left(|\beta(m)|^2+\frac{1}{\lambda_{max}(m)}\right)-\sum_{i=1}^{M}\frac{1}{\lambda_{max}(i)}\\ &= MP_{max}\end{aligned} \quad (28)$$

Finally, we obtain the following set of equalities:

$$|\beta(m)|^2 = P_{max}-\frac{1}{\lambda_{max}(m)}+\frac{1}{M}\sum_{i=1}^{M}\frac{1}{\lambda_{max}(i)} \quad (29)$$

for $m=1,...,M$.

IV. User Selection Algorithm

We propose here an iterative algorithm to solve the maximization problem in Section III. Firstly, the per-user power constraint given in (13) has been utilized to solve the problem, i.e. maximizing the per-user sum capacity under the constraint of maintaining the per-user power constraint lower than P_{max} for all users. In this case, the transmitted power through all SUs is given by:

$$|\beta(m)|^2 = P_{max}, \qquad m = 1, ..., M \tag{30}$$

but it is not the optimal solution. Besides, from (29), $|\beta(m)|^2$ can have values higher than P_{max} which contradicts condition (13). To optimally solve this problem, one should adopt this solution:

$$\begin{aligned} |\beta(m)|^2 &= P_{max} \qquad \text{if } |\beta(m)|^2 > P_{max} \\ |\beta(m)|^2 &= P_{max} - \frac{1}{\lambda_{max}(m)} + \frac{1}{M}\sum_{i=1}^{M}\frac{1}{\lambda_{max}(i)} \quad \text{else} \end{aligned}$$

Therefore, it will be shown later from simulation results that adopted solution can approximate very well the per-user sum capacity with optimal power allocation.

SUs offer the opportunity to improve the system throughput by detecting the PU activity and adapting their transmissions accordingly while avoiding the interference to the PU by satisfying the QoS constraint. The motivation behind the proposed technique is that SUs can be selected following the dominant eigenvalues under the constraint of maintaining the outage probability of the PU not degraded [10]. Our goal is to determine, under the assumption that the PU is oblivious to the presence of the cognitive users, the maximum number of cognitive communication links allowed in such a system. The optimization problem can therefore be expressed as follows:

$$\text{Find } \{|\beta(1)|^2 ... |\beta(M)|^2\} = \arg\max \mathrm{C}_{su} \tag{31}$$

subject to:

$$\begin{cases} |\beta(m)|^2 \leq P_{max} & \forall m = 1, ..., M \\ \sum_{i=1}^{M} |\beta(i)|^2 \leq M P_{max} \\ P_{out} = Prob\{\mathrm{C}_{pu} \leq R_{pu} | R_{pu}, q\} \leq q \end{cases} \tag{32}$$

In what follows, we will present an algorithm of user selection strategy in the context of CRN. An iterative approach is adopted throughout the algorithm. The algorithm is first initialized with a number of transmitter SUs equal to M. Each SU simultaneously measures his transmit and receive beamvector based on (29) and (11), respectively. Then, the SNIR and SNIR$|_{max}$ values can be computed using (8) and (12), and depending on whether the SU remains active or inactive during the next time slot based. Similarly, at every iteration, the PU verifies the outage probability constraint based on the resulting resource allocation. The goal here is to maximize the sum capacity (C_{su}) subject to maximize the number of cognitive communication links allowed in such a system. The algorithm is run until the secondary sum power stabilizes for a given number of iterations. The last SU entering in the system is removed from the transmission.

V. Numerical Results

To go further with the analysis, we resort to realistic network simulations. Specifically, we consider a CRN with one PU and M SUs attempting to communicate during a transmission, subject to mutual interference. A hexagonal cellular system functioning at 1.8 GHz with a primary cell of radius $R = 1000$ meters and a primary protection area of radius $R_p = 600$ meters is considered. Secondary transmitters may communicate with their respective receivers of distances $d < R_p$ from the BS. Channel gains are based on the COST-231 path loss model [14] including log-normal shadowing with standard deviation of 10 dB, plus fast-fading assumed to be i.i.d. circularly symmetric with distribution $\mathcal{CN}(0, 1)$.

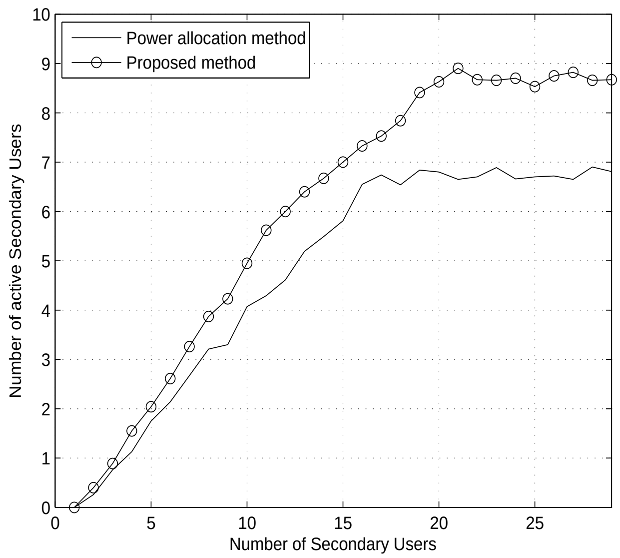

Fig. 2. Number of active SUs vs. number of SUs at rate = 0.3 bits/s/Hz and an outage probability = 1% in the uplink (the uplink centralized binary power allocation method [15] and the proposed method).

In Fig. 2, the number of active SU links under the proposed algorithm as a function of the total number of users, for a target outage probability = 1% and a rate = 0.3, is depicted. It can be seen from the figure that increasing the number of SUs yields improvements in the number of active users. Asymptotically, i.e., as the number of SUs goes large, the number of active SUs keeps constant due to the influence of interference impairments on the PU's QoS.

We also compare the results obtained by the proposed method to those obtained using the centralized binary power allocation [15]. It can be observed that the proposed scheme allows almost 2 additional active SUs more than the binary power allocation scheme. As an example, we get 9 and 7 active SUs for 25 potential SUs for the proposed method and the one presented in [15], respectively.

In order to validate our theoretical derivation, we also compare the outage probability defined in (17) for both the proposed method and the centralized binary power allocation method. As an example we carry out simulations at PU rate = 0.3 bits/s/Hz. First, it is clear from Fig. 3 that the outage probability using both schemes are similar. We also remark

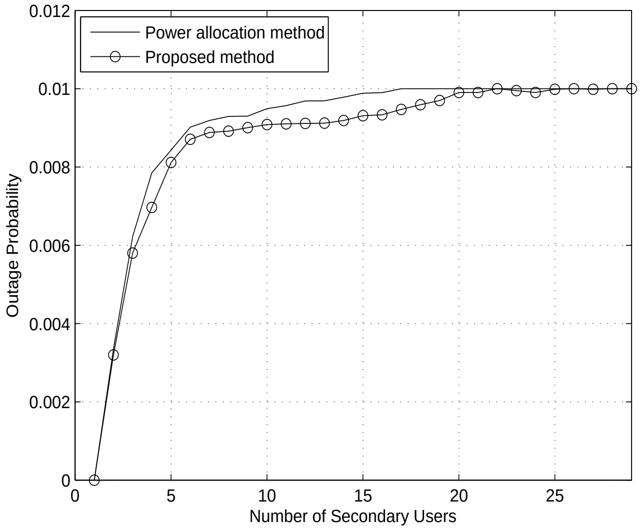

Fig. 3. The uplink outage probability as function of the number of SUs for a target outage probability = 1% and a rate = 0.3 bits/s/Hz (the uplink centralized binary power allocation method [15] and the proposed method).

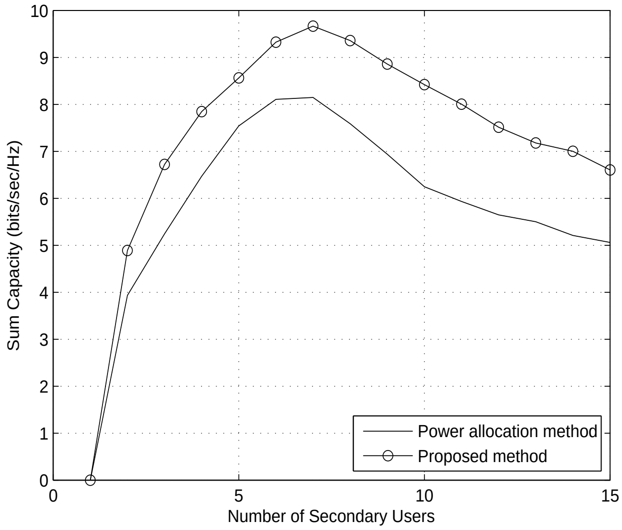

Fig. 4. Sum capacity vs. number of SUs at rate = 0.3 bits/s/Hz and an outage probability = 1% in the uplink (the uplink centralized binary power allocation method [15] and the proposed method).

that, for the outage probability of interest (i.e., at rate = 0.3 bits/s/Hz), the number of allowed SUs to transmit is equal to 20 SUs. This is exactly what Fig. 2 shows in the saturation state.

Fig. 4 depicts the sum capacity for the SU links. As expected, initially increasing the number of SUs yields a significant increase in capacity because the increase in the degrees of freedom more than compensates for the decrease in SINR due to interference. However, reaching a certain number of SUs, the sum capacity decreases again as the number of SUs increases further. Notice here that, as the primary cell radius R and the primary protection area radius R_p decrease, the sum capacity becomes more sensitive to the interference impairments leading to a significant decrease in the secondary sum rate. The current curve claims that in CRNs without interference cancelation abilities, when one attempts to maximize the number of active SUs, the cognitive sum capacity degrades asymptotically. Typically, there is a fundamental trade-off between cognitive capacity maximization and number of active SUs maximization.

VI. Conclusion

In this paper, we have explored the idea of combining user selection with an efficient transmit and receive beamforming technique to maximize the SU rate while maintaining a QoS to a PU. First, SUs are pre-selected so as to maximize the per-user sum capacity. Then, the PU verifies the outage probability constraint and a number of SUs are selected from those pre-selected SUs. We showed that the proposed approach exhibits a significant number of cognitive users able to transmit while constraining interference to guarantee QoS for the PU. Simulation results were carried out based on a realistic network setting. As a future work, it is of major interest to the resource allocation based on spatial interference pattern [16]. We will introduce the game theory concept to define a new user selection strategy in the context of CRN.

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