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On Green Cognitive Radio Cellular Networks: Dynamic Spectrum and Operation Management

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***Abstract*—We study a profit maximization problem related to cognitive radio cellular networks in an environmentally-friendly framework. The objective of the primary network (PN) and secondary network (SN) is to maximize their profits while respecting a certain carbon dioxide (CO_2) emissions threshold. In this study, the PN can switch off some of its base stations (BSs) powered by mircogrids, and hence leases the spectrum in the corresponding cells, to reduce its footprint. The corresponding users are roamed to the SN infrastructure. In return, the SN receives a certain roaming cost and its users can freely exploit the spectrum. We study two scenarios in which the profits are either separately or jointly maximized. In the disjoint maximization problem, two low complexity algorithms for PN and SN BS on/off switching are proposed to maximize the profit per CO_2 emissions utility and determine the amount of the shared bandwidth. In the joint maximization approach, the low complexity algorithm is based on maximizing the sum of weighted profits per CO_2. Selected numerical results illustrate the collaboration performance versus various system parameters. We show that the proposed algorithms achieve performances close to those obtained with the exhaustive search method, and that the roaming price and the renewable energy availability are crucial parameters that control the collaboration of both networks.**

***Index Terms*—Collaborative cellular networks, dynamic spectrum management, green cognitive radio, microgrid.**

I. Introduction

Due to the recent interest in energy efficient cellular networks, many mobile operators are adopting an environmentally friendly management of their cellular networks [1]. The main focus is on the radio access networks (RANs) since around 60% of the energy is consumed by the base stations (BSs) [2]. From the operators' point of view, being energy-efficient is not only about environment viability concerns, but also about reducing the expenses and maximizing the profit. Hence, there are growing efforts to develop more energy-efficient networks. Mainly, the issue of the energy consumption is becoming a concern due to three main reasons: i) the carbon dioxide (CO_2) emissions of the ICT industry is relatively high with around 2% of the global emission [3] whereas the cellular networks present 0.2% [4], ii) the high energy consumption affects the profit of mobile operators due to heavy electricity bills [5], iii) reducing the energy consumption of mobile stations provides longer operation time due to reduced battery capacity [6].

Therefore, there are tremendous efforts to introduce and spread alternative sources to power the RAN [7], [8]. Adopting such resources led to a microgrid design of the cellular network [9]. The microgrid is a promising solution to power BSs in places where on-grid energy is unreachable and renewable energy are available. This microgrid concept is based on connecting one or more BSs to a local energy source involving one or more renewable energy, [10], in addition to the usual fuel generated electricity. In this case, these off-grid BSs become autonomous and less fuel energy is consumed. In [11], different power supply models for off-grid BSs were presented. Powering cellular networks with renewable energy sources was presented in [12], [13]. In addition, dynamic pricing of energy was discussed in [14].

From another side, due to the spectrum scarcity, the cognitive radio (CR) networks were introduced to solve spectrum problems [15]. In fact, new wireless technologies require high bandwidth that is either unavailable as the spectrum is overloaded or extremely expensive. Hence, the spectrum becomes a scarce resource [16]. The CR concept was introduced by Mitola [17]. In this concept, the unlicensed/secondary users share the spectrum with the licensed/primary users without harming the primary quality of service (QoS) [18], [19].

Consequently, the energy consumption and the spectrum scarcity are considered as the main challenges facing next generation, i.e., the fifth generation (5G), cellular systems [20]–[22]. As a result, dynamic spectrum management as well as energy-efficient and environment-aware design should be jointly considered in the design of the next generation cellular networks [23]. In the literature, few studies focused on green cooperation between primary and secondary networks [24], [25]. In [24], the authors studies the cooperation of cognitive users within the TV bands In [26], a cognitive cellular network setting was studied where the PN is minimizing its energy consumption while the SN maximizes its achievable rate. In [27], the authors studied the green cooperation between two operators in which the objective is to minimize the fossil fuel cost. The main objective of these studies is to achieve maximum profit for both operators. Although they aim to optimize the green cooperation between both networks, these studies do not consider the microgrid aspects with dynamic pricing in their models and do not focus on the CO_2 emissions as a fundamental metric for green communications.

The novelty of this paper is proposing spectrum-aware and energy-aware operation scheme for cellular networks in a CR context. The main idea is to exploit the existence of the SNs in order to ensure additional energy savings and CO_2 emissions reduction [28]. In this framework, we formulate an optimization problem that maximizes the profits of the PN and the SN subject to CO_2 emissions and QoS constraints. The PN is allowed to switch off a certain number of BSs to reduce the CO_2 emissions without being below the tolerated number of users in outage. Hence, some of the primary users will be roamed to the neighbors SN BSs. In return, the latter BSs can freely exploit the spectrum and the PN pays a roaming cost to the SN. Two cases of the profits maximization are investigated: a disjoint approach, i.e., decentralized profit maximization, and a joint approach, i.e., centralized profit maximization. In the decentralized approach, lower exchange of information between both operators is considered. First, the PN optimizes its BSs operation and transfer the output to the SN which adopts its operation accordingly. In the centralized approach, both networks jointly optimize their operations as a single virtual network.

Moreover, we analyze the collaboration between PN and SN in terms of spectrum sharing and spectrum leasing [29]. A low complexity algorithm based on profit per CO_2 emissions metric is proposed to solve the combinatorial optimization problem to determine the best active BS combinations and the corresponding fractions of bandwidths related to the PN and SN. The profit maximization is performed by considering the renewable energy availability and the dynamic energy pricing at the microgrid levels. Through different simulations, we investigate the system performance versus various parameters and compare the performance of the proposed algorithm to those of the exhaustive search (ES) solutions. Most precisely, the contributions of the paper can be summarized as follows:

- A green overlay collaboration model for cognitive cellular networks is investigated where PN is allowed to offload its users to neighbor SN BSs when its BSs are switched off. In return, the SN uses the spectrum leased in the corresponding primary cells in addition to extra profit income due to the roaming operation. The SN can switch off some of its BSs if the CO_2 constraint is not respected.
- The objective of both networks is to maximize their profit metrics that depend on several parameters such as the service revenue, energy cost, spectrum leasing/sharing cost, and roaming cost, subject to QoS constraint and a CO_2 emissions limit. Since both networks are serving a common geographical area, the total CO_2 emissions are shared between both networks and two approaches are considered:
  - A disjoint, or decentralized, approach where the priority is first given to PN to find the active BSs that maximize its profit with respect to a partial CO_2 threshold, then, SN performs a best-effort approach to maximize its profit.
  - A joint, or centralized, approach where a weighted profit maximization metric is considered. The optimization is performed by a third party, i.e., a broker, that maximizes both profits in real time. This approach avoids iterative optimization that may delay the SN in case it provides real-time service.
- A low complexity algorithm for BS activation/deactivation and spectrum management is proposed to be employed instead of the complex ES method. The proposed algorithm is applied to both approaches with some minor modifications. The proposed algorithm is based on a profit per CO_2 emissions metric allowing to reach a sub-optimal solution close to the ES one.
- Multiple numerical simulations are proposed to investigate the performance of the disjoint PN/SN cooperation for various parameters such as the roaming price, CO_2 partial emission, renewable energy availability. In addition, we evaluate the joint approach performance with respect to the PN/SN weights.

The rest of this paper is organized as follows. In Section II, we describe the system model. In Section III, we present the problem formulation. In Section IV, we present the proposed algorithms to maximize the PN and SN profits in a decentralized manner. In Section V, we present the algorithm maximizing the sum weighted PN-SN profits in a centralized manner. Numerical results are presented in Section VI. Finally, the paper is concluded in Section VII.

II. System Model and Green Aspects

A. Cellular Network Model

We study the collaboration between two mobile operators deploying cellular networks in the same geographical area. The first operator, the PN, is licensed to use the frequency bandwidth denoted by W. The second operator, the SN, is allowed to share the spectrum with the PN in change for eventual collaboration when needed. Both PN and SN have N_{BS} BSs that cover the same area of interest to serve a total of N_p and N_s users, respectively. The PN and SN are modeled as hexagonal cells with a tri-sectoral transmission in which the area covered by each BS is divided into three equal areas. The secondary BSs are deployed such as the distance between the secondary BS and the closest primary BS is equal to the cell radius so that the interference is minimal as shown in Fig. 1.(a). That is, the secondary BSs are deployed in the intersection of three primary cells to cover the same region and having minimal interference. In each cell, the PN and SN users are randomly placed with coordinates (x_p, y_p) and (x_s, y_s) and benefit from one of the different services provided by each network, denoted by Σ_p and Σ_s, respectively. We denote by $N_{i,j}^{(\sigma)}$ the number of users of network i, where $i \in \{p, s\}$ denotes the PN and SN, respectively, and $\sigma, \sigma = 1, \cdots, \Sigma_i$ designates the type of provided service. The users of a network i using a given service σ are placed according to a given joint probability density function (pdf) denoted by $f_{i,\sigma}(x_i, y_i)$. On the other side, at the network i, the power consumed at the j-th BS is denoted by $P_{i,j}$. This power is computed as [30]:

$$P_{i,j} = a_i \sum_{\sigma=1}^{\Sigma_i} \sum_{k=1}^{N_{i,j}^{(\sigma)}} p_{i,j}^{(k,\sigma)} + b_i, \tag{1}$$

where $p_{i,j}^{(k,\sigma)}$ is the transmit power allocated to user k using service σ in the j-th BS, a_i is a coefficient reflecting the

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amplifier and the feeder losses in the network i, and b_i is a constant power consumed independently of the transmit power [31]. This parameter includes the signal processing (analog to digital converters (ADC), filters, mixers, amplifiers, etc.), battery backup, and cooling. Note that a_i and b_i might differ from a network to another depending on the nature of equipment used by each network.

In this study, we are considering a downlink planning problem based on average statistics. Therefore, we compute the average power per user per service σ, denoted by $\overline{p}_{i,j}^{(\sigma)}$. Hence, equation (1) can be re-written as $P_{i,j} = a_i \sum_{\sigma=1}^{\Sigma_i} N_{i,j}^{(\sigma)} \overline{p}_{i,j}^{(\sigma)} + b_i$, where $\overline{p}_{i,j}^{(\sigma)}$ denotes the average transmitted power per service of the j-th BS in order to serve users using service σ. The average transmit power per user for a given σ is expressed as [30]:

$$\overline{p}_{i,j}^{(\sigma)} = \frac{P_{\min}^{(\sigma)}}{K} \mathbb{E}_{i,\sigma}[d_{\bar{i},j}^{\nu}], \quad (2)$$

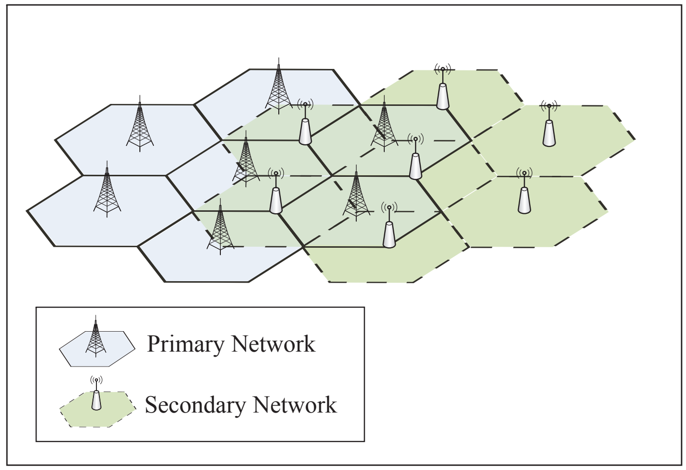
where $P_{\min}^{(\sigma)}$ is the minimum power to be received by each user using service σ in order to ensure its QoS requirement, K is a parameter representing the effects of BS antenna settings, carrier frequency, and propagation environment, and ν is the path loss exponent. The term $\mathbb{E}_{i,\sigma}[d_{\bar{i},j}^{\nu}]$ denotes an average distance function between the j-th BS of network $\bar{i}$, where $\bar{i} = s$ if $i = p$ and $\bar{i} = p$ if $i = s$ depending on the users and the serving BS, and the users of network i using service σ connected to this BS. This average distance function is computed using the distribution of users using service σ within cell j of network i, denoted by $C_{i,j}$, as follows:

$$\mathbb{E}_{i,\sigma}[d_{\bar{i},j}^{\nu}] = \iint_{C_{\bar{i},j}} \left((u - x_{\bar{i},j})^2 + (v - y_{\bar{i},j})^2\right)^{\frac{\nu}{2}} f_{i,\sigma}(u,v) du dv, \quad (3)$$

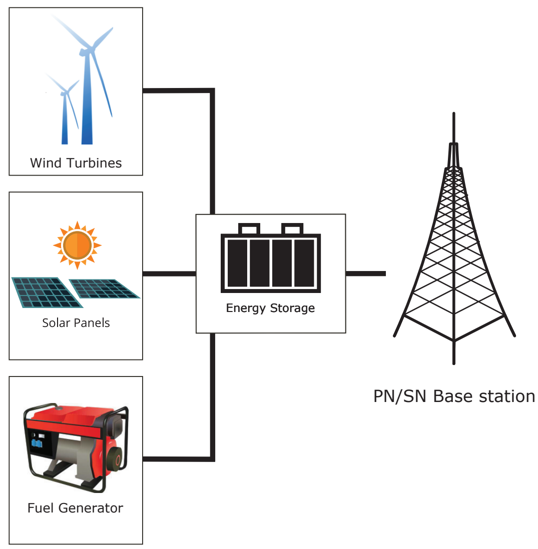
where (u, v) are the random location coordinates of a user using service σ belonging to network i following the distribution $f_{i,\sigma}(u, v)$. Note that each BS has a certain capacity, denoted by $\overline{N}_i$, $i \in \{p, s\}$, representing the maximum number of users that can be served simultaneously. For instance, this can be due to a limited number of channel carriers. We assume that, before collaboration, PN and SN are well-planned, i.e., $N_{p,j} \leq \overline{N}_p$ and $N_{s,j} \leq \overline{N}_s$ where $N_{i,j}$ denotes the total number of users of network i connected to the j-th BS such that $N_{i,j} = \sum_{\sigma=1}^{\Sigma_i} N_{i,j}^{(\sigma)}$. However, since there will be cases of PN users roamed to the SN, the PN outage constraint as well as the maximum capacity constraints at each secondary BS has to be respected. In order to meet the users' QoS in terms of data rate, the following inequality has to be satisfied:

$$w_{i,\sigma} \log_2 \left(1 + \frac{P_{\min}^{(\sigma)}}{w_{i,\sigma} N_0}\right) \geq r_{i,\sigma}. \quad (4)$$

where N_0 denotes the noise power per unit of bandwidth and $w_{i,\sigma}$ denotes the fraction of bandwidth allocated to each user using service σ of network i achieving the target rate for the average transmit power $\overline{p}_{i,j}^{(\sigma)}$ given by (2). In other words, the achieved data rate has to be greater than or equal to the required data rate per user for the service σ offered by network i, denoted by $r_{i,\sigma}$. It has been shown in [27] that $w_{i,\sigma}$



(a) Model of cellular CR network.



(b) The microgrid model.

Fig. 1: System model of cellular CR network with the microgrid at each BS.

is given by:

$$w_{i,\sigma} = -\frac{\frac{P_{\min}^{(\sigma)}}{N_0}}{1 + \frac{P_{\min}^{(\sigma)}}{r_{i,\sigma} N_0} \mathcal{W}_{-1}\left(-\frac{r_{i,\sigma} N_0}{P_{\min}^{(\sigma)}} e^{-\frac{r_{i,\sigma} N_0}{P_{\min}^{(\sigma)}}}\right)}, \quad (5)$$

where $\mathcal{W}_{-1}(\cdot)$ is the lower branch of the W-Lambert function and defined in $[-\frac{1}{e}, 0]$ [32]. We verify that $\frac{P_{\min}^{(\sigma)}}{r_{i,\sigma} N_0} \mathcal{W}_{-1}\left(-\frac{r_{i,\sigma} N_0}{P_{\min}^{(\sigma)}} e^{-\frac{r_{i,\sigma} N_0}{P_{\min}^{(\sigma)}}}\right) < -1$ so that the fraction of bandwidth expression in (5) is non-negative.

B. Green Aspects in the Cellular Networks

Although the objective of both networks is to maximize their profits, we present, in this study, four aspects related to green communications that influence the PN-SN collaboration:

1) Renewable Energy Generation: We propose to introduce renewable energy as an alternative energy source (e.g., wind, solar, etc.) to power the BSs. As illustrated in Fig. 1.(b), each BS is powered by a microgrid generating energy from a green source, denoted by $\mathcal{E}_{i,j}^{(g)}$, for the j-th BS of network i. In the case of lack of renewable energy, the microgrid buys the extra amount of required energy from the traditional electrical grid, assumed to be from a fossil fuel source, such that the energy consumption of the j-th BS is satisfied. In other words, the amount of energy procured from the grid is expressed as $\max(\mathcal{E}_{i,j} - \mathcal{E}_{i,j}^{(g)}, 0)$, where $\mathcal{E}_{i,j}$ is the energy consumption of the j-th BS of network i during its operation time T and equals to $\mathcal{E}_{i,j} = P_{i,j}T$.

2) Dynamic Energy Pricing: We consider that the microgrid imposes a constant price, denoted by $c^{(g)}$, for each unit of consumed *green* energy. However, as fossil fuel is consumed from the electrical grid, the energy price imposed by the microgrid is modeled as an increasing function of the fossil fuel consumption of the BS [33]. We adopt the following energy cost function $c_{i,j}$ imposed to each BS j of network i:

$$c_{i,j} = \begin{cases} c^{(g)}, & \text{if } \mathcal{E}_{i,j} \leq \mathcal{E}_{i,j}^{(g)}, \\ c^{(g)} + f(\mathcal{E}_{i,j}), & \text{if } \mathcal{E}_{i,j} > \mathcal{E}_{i,j}^{(g)}, \end{cases} \quad (6)$$

where $f(.)$ is a price function that varies with the consumption. The function $f(.)$ could follow a linear or quadratic behavior depending on the sensitivity of the fossil fuel cost to the real-time demand of the BS. Note that the imposed energy price on each BS depends on its total power consumption and the renewable energy availability during the operation time Δt. The dynamic energy pricing forces consumers to minimize their fossil fuel consumption and exploit as much as possible the green energy instead.

3) Limited CO_2 emissions: The equivalent amount of CO_2 emitted by all BSs (belonging to both networks: PN and SN) is limited by a certain emission threshold denoted by $\overline{CO_2}$. Note that the equivalent CO_2 emissions is computed as a function of the fossil fuel consumption considering the nature of the energy source [34]. For example, wood source and a refinery gas emit 0.39 and 0.24 kg of CO_2 per 1 KWh, respectively [34]. Note that the CO_2 emissions can be also evaluated using a quadratic penalty function [35] which is adopted in this paper. The CO_2 emissions penalty function at a BS j of network i, denoted by $\mathcal{F}_{i,j}^{CO_2}$, is given as follows [35]:

$$\mathcal{F}_{i,j}^{CO_2} = \begin{cases} 0, & \text{if } \mathcal{E}_{i,j} \leq \mathcal{E}_{i,j}^{(g)}, \\ \phi_i(\mathcal{E}_{i,j} - \mathcal{E}_{i,j}^{(g)})^2 + \psi_i\left(\mathcal{E}_{i,j} - \mathcal{E}_{i,j}^{(g)}\right), & \text{if } \mathcal{E}_{i,j} > \mathcal{E}_{i,j}^{(g)}, \end{cases} \quad (7)$$

where ϕ_i and ψ_i are the pollutant coefficients related to the fossil fuel source powering the BSs of network i. The total CO_2 emissions, i.e., the sum of $\mathcal{F}_{i,j}^{CO_2}$ is denoted by $\mathcal{F}_{i}^{CO_2}$.

Note that the green sources do not produce CO_2 emissions which encourage the operators to adopt these sources when there is a CO_2 threshold imposed be the governments.

4) BSs on/off switching: We consider that mobile operators are able to switch off some of their BSs. In this cognitive framework, we assume that users initially connected to switched off PN BSs can be roamed to a neighbor SN BSs. Consequently, the PN will reduce the energy consumption and the CO_2 emissions of the overall network. In addition, the SN is forced to switch off some of its BSs in order to meet the CO_2 emissions requirement. Note that, the SN BSs serving the PN users need to stay active. In return, SN imposes a roaming price to compensate the extra energy cost caused by the PN roamed users. The SN is allowed to switch off some BSs in some particular cases that will be described in the sequel. In order to apply the BS on/off switching, we introduce the binary variables $\epsilon_{i,j}$ denoting the status of the j-th BS of network i, i.e., $\epsilon_{i,j} = 1$ if the j-th BS is switched on, otherwise, $\epsilon_{i,j} = 0$. If a BS j is switched off, we consider that it does not consume energy, i.e., $\mathcal{E}_{i,j} = 0$. We denote by $\boldsymbol{\epsilon}_p$ and $\boldsymbol{\epsilon}_s$ the vectors corresponding to the PN and SN BS on/off statuses, respectively.

Given these four *green* aspects, the PN has to preserve a certain QoS of the network, i.e., the total number of served users (directly served or roamed) to respect a certain outage P_{out}. Otherwise, since the objective is to maximize the profit, the PN can reach a case in which it leases the spectrum to earn money instead of serving its users. Note that the outage constraint is not imposed to SN for two reasons. First, the available resources (spectrum, allowed CO_2 emissions, etc.) are highly dependent on the PN activity. For instance, in some cases, the SN may be forced to switch off some of its BSs to respect the total CO_2 emissions constraint. Thus, we cannot force the SN to serve its users all the time. The second reason is that the PN may roam users that have high priority and must be served by the SN. For these reasons, the SN may be unable to serve all its users. Nevertheless, the SN obtain a roaming reward instead.

III. Problem Formulation and Constraints

The proposed collaborative framework represents a good opportunity for mobile operators to enhance their profits while behaving green. This is performed by either reducing their energy costs or sharing their licensed spectrums. The proposed scenario can be interpreted as follows; we consider a single mobile operator deploying a well-planned cellular network (i.e., QoS maintained and tolerated CO_2 emissions respected) in a given geographical area. An unlicensed secondary operator aims to provide particular services to their users by exploiting the same frequency band. A mutually beneficial collaborative scheme is a solution that can be adopted by both operators to meet their objectives while respecting the same initially tolerated CO_2 emissions.

A. Dynamic Spectrum Management

The cooperation between the PN and SN is based on the management of the available bandwidth W. This management includes two modes of collaboration: the spectrum leasing and the spectrum sharing:

- **Spectrum leasing**: When the PN traffic is low or the $j-$th BS is decided to be inactive, the PN can partially or fully lease the non-used spectrum to the SN with a price denoted by p_{sl}. We denote by $\beta_{p,j}$, $0 \leq \beta_{p,j} \leq 1$, the

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fraction of the spectrum W that can be leased to the j-th SN BS. Hence, $\beta_{p,j} \times W$ is the available bandwidth that the SN is free to use without caring about interference. Note that if the j-th PN BS is off, $\beta_{p,j}$ is set equal to 1. In addition, the SN is not forced to exploit the whole fraction $\beta_{p,j} \times W$ but cannot go beyond this fraction. Thus, we define the variable $\beta_{s,j}$ as the bandwidth fraction needed by the SN where $0 \leq \beta_{s,j} \leq \beta_{p,j}$.

- **Spectrum sharing**: When the j-th BS remains active, the PN can share part of the spectrum with the SN. This part corresponds to $(1 - \beta_{p,j}) \times W$ with a price denoted by p_{ss}. In this spectrum sharing mode, the SN transmission needs to respect an interference threshold imposed by PN denoted by I_{th}.

Although the prices p_{sl} and p_{ss} are different, they are assumed to be constant for all the BSs.

B. Primary Network Profit Expression and Constraints

The PN focuses on maximizing its profit while respecting the service outage and the CO_2 emission constraints. We denote by Π_p the profit corresponding to the PN operation which is defined as:

$$\Pi_p = \sum_{j=1}^{N_{\text{BS}}} \Pi_{p,j} = \underbrace{\sum_{j=1}^{N_{\text{BS}}} \sum_{\sigma=1}^{\Sigma_p} p_{p,\text{op}}^{(\sigma)} \left(N_{p,j}^{(\sigma)} + N_{p,j}^{(\text{roamed},\sigma)} \right)}_{\text{Service profit}}$$
$$+ \underbrace{\sum_{j=1}^{N_{\text{BS}}} (1 - \epsilon_{p,j}) \left(p_{sl} \beta_{s,j} W - p_{\text{roam}} N_{p,j}^{(\text{roamed})} \right)}_{\text{Inactive BS profit}}$$
$$+ \underbrace{\sum_{j=1}^{N_{\text{BS}}} \epsilon_{p,j} \left(p_{ss}(1 - \beta_{s,j}) W + p_{sl} \beta_{s,j} W - c_{p,j} \mathcal{E}_{p,j} \right)}_{\text{Active BS profit}}, \quad (8)$$

where $\Pi_{p,j}$ is the profit gained from the j-th BS, $p_{p,\text{op}}^{(\sigma)}$ is the operation price paid by every single served PN user using service σ, $N_{p,j}^{(\text{roamed},\sigma)}$ is the number of roamed users using service σ offloaded from the j-th PN BS to the j-th BS belonging to the SN, p_{roam} is the roaming price paid by the PN to the SN for every single roamed and served user, and $c_{p,j}$ represents the energy cost that scales with the BS energy consumption $\mathcal{E}_{p,j}$. The total number of roamed users $N_{p,j}^{(\text{roamed})} = \sum_{\sigma=1}^{\Sigma_p} N_{p,j}^{(\text{roamed},\sigma)}$. Note that $\beta_{s,j}$ cannot be determined by the PN since it is optimized by the SN after having the optimized parameters of the PN problem. One way to overcome this dependency is to adopt a certain value of $\beta_{s,j}$ that will give approximately the same PN profit. We choose, for instance, $\beta_{s,j} = \beta_{p,j}$ which means that the PN assumes that the SN will exploit all the leased fractions. This assumption is valid for two reasons. Firstly, the term $p_{sl}\beta_{s,j}W$ is common for the active or inactive status of the given j-th PN BS. That is, both profits will be shifted if the $\beta_{s,j} < \beta_{p,j}$. This eventual shift does not affect the proposed algorithm in the next Section since it is based on comparing these two profits for each BS. Secondly, the term $p_{ss}(1 - \beta_{s,j})W$ that characterizes the inactive status gives a lower bound of the profit when $\beta_{s,j} = \beta_{p,j}$ which means that even if $\beta_{s,j} < \beta_{p.j}$, the corresponding profit is higher.

Maximizing the PN profit is subject to three constraints:

- **Roamed users constraint:** the number of roamed users cannot exceed the number of users that can be served by the SN $\overline{N}_s$, called the SN service capacity, i.e.,

$$0 \leq N_{p,j}^{(\text{roamed})} \leq \overline{N}_s. \quad (9)$$

- **Service outage constraint:** the number of users in outage has to be less than a certain threshold. A user is considered in outage when it is not being allocated to any BS (i.e., primary or secondary BS). For instance, this can be caused by a limited coverage or insufficient SN resources. Thus, the PN QoS constraint can be written as

$$\frac{N_p - \sum_{j=1}^{N_{\text{BS}}} \left(N_{p,j} + N_{p,j}^{(\text{roamed})} \right)}{N_p} \leq P_{\text{out}}. \quad (10)$$

where P_{out} corresponds to the ratio of the number of users allowed to be in outage to the total number of users.

- **CO_2 emissions penalty constraint:** the total CO_2 emissions of PN has to be below the threshold C_{th} imposed by the regulator, and is given as follows

$$\mathcal{F}_p^{\text{CO}_2} = \sum_{j=1}^{N_{\text{BS}}} \mathcal{F}_{p,j}^{\text{CO}_2} \leq C_{th}. \quad (11)$$

The value of C_{th} scales linearly with the number of BSs N_{BS}. In fact, it can correspond to product of the quantity of CO_2 allowed to be emitted within the area of one cell and the number of cells. Depending on the investigated scenario, this constraint can be updated such that the total CO_2 emissions due to the cognitive system operation (PN and SN) is below the total threshold imposed by the regulator $\overline{\text{CO}_2}$. In the sequel, we denote by $\overline{C_{th}}$ the maximum SN CO_2 emissions tolerated by the regulator such that $C_{th} + \overline{C_{th}} = \overline{\text{CO}_2}$.

C. Secondary Network Profit Expression and Constraints

The objective of the SN is also maximize its profit by either sharing the spectrum or exploiting the leased spectrum. However, the SN is limited to the PN decision variables specifically $\beta_{p,j}$ and $N_{p,j}^{(\text{roamed})}$ for $j = 1, \cdots, N_{\text{BS}}$. The profit of the SN is given by

$$\Pi_s = \underbrace{\sum_{j=1}^{N_{\text{BS}}} \sum_{\sigma=1}^{\Sigma_s} \epsilon_{s,j} p_{s,\text{op}}^{(\sigma)} N_{s,j}^{(\sigma)}}_{\text{Service profit}} - \underbrace{\sum_{j=1}^{N_{\text{BS}}} \epsilon_{s,j} c_{s,j} \mathcal{E}_{s,j}}_{\text{Energy cost}}$$
$$+ \underbrace{\sum_{j=1}^{N_{\text{BS}}} \epsilon_{s,j} (1 - \epsilon_{p,j}) \left(p_{\text{roam}} N_{p,j}^{(\text{roamed})} - p_{sl} \beta_{s,j} W \right)}_{\text{Inactive PN BS profit}}$$
$$- \underbrace{\sum_{j=1}^{N_{\text{BS}}} \epsilon_{s,j} \epsilon_{p,j} \left(p_{ss}(1 - \beta_{s,j}) W + p_{sl} \beta_{s,j} W \right)}_{\text{Active PN BS profit}}, \quad (12)$$

where $p_{s,\mathrm{op}}^{(\sigma)}$ is the operation price paid by served SN users using service σ. Note here that, unlike PN, the profit corresponding to a switched off secondary BS is zero as a switched off BS will serve any users. The optimization variables of the secondary problem, for $j = 1, \cdots, N_{\mathrm{BS}}$, are $\epsilon_{s,j}, \beta_{s,j}, N_{s,j}$. The SN problem involves five constraints defined as follows:

- **Transmit power budget constraint:** the total transmit power of the secondary BS, i.e., $\sum_{\sigma=1}^{\Sigma_s} N_{s,j}^{(\sigma)} \overline{p}_{s,j}^{(\sigma)} + \sum_{\sigma=1}^{\Sigma_p} N_{p,j}^{(\mathrm{roamed},\sigma)} \overline{p}_{p\to s,j}^{(\sigma)}$ where $\overline{p}_{p\to s,j}^{(\sigma)}$ is the average transmit power needed to serve the roamed users of PN in cell j using service σ by the j-th BS of SN, must be below the available power budget, denoted by $\overline{P}_s$, and is expressed as

$$\sum_{\sigma=1}^{\Sigma_s} N_{s,j}^{(\sigma)} \overline{p}_{s,j}^{(\sigma)} + \sum_{\sigma=1}^{\Sigma_p} N_{p,j}^{(\mathrm{roamed},\sigma)} \overline{p}_{p\to s,j}^{(\sigma)} \leq \overline{P}_s. \quad (13)$$

  Although the network is well-planned, this constraint has to be considered as the roamed PN users may cause an excess of transmit power consumption.
- **Interference constraint:** the interference caused by SN transmission on the PN BS needs to be below a certain threshold denoted by I_{th}. This constraint is valid when $\epsilon_{p,j} = 1$ in the spectrum sharing scenario. The following interference constraint in each cell has to be satisfied:

$$\overline{p}_{s,j}^{(\sigma)} \frac{K}{\mathbb{E}_{p,\sigma}[d_{s,j}^{\nu}]} \leq I_{\mathrm{th}}, \forall j = 1, \cdots, N_{\mathrm{BS}}. \quad (14)$$

  Hence, the fraction of bandwidth $w_{s,\sigma}$ to be allocated to each secondary user of the SN using service σ in the spectrum sharing scenario has to satisfy (4) with a transmit power given by $\overline{p}_{s,j}^{(\sigma)} = \min\{P_{\min}^{(\sigma)}, I_{\mathrm{th}}\} \times \frac{\mathbb{E}_{p,\sigma}[d_{s,j}^{\nu}]}{K}$.
- **Service capacity constraint:** the total number of served users including the PN roamed users needs to be below the SN service capacity per BS. In other words,

$$N_{s,j} \leq \overline{N}_s - N_{p,j}^{(\mathrm{roamed})}, \forall j = 1, \cdots, N_{\mathrm{BS}}. \quad (15)$$

  Note that in this constraint the variable to be optimized is $N_{s,j}$ whereas in (9) the variable is $N_{p,j}^{(\mathrm{roamed})}$.
- **CO_2 emissions penalty constraint:** the CO_2 emissions of the SN is below the corresponding fraction allowed CO_2 in the area as follows:

$$\mathcal{F}_s^{CO_2} = \sum_{j=1}^{N_{\mathrm{BS}}} \mathcal{F}_{s,j}^{CO_2} \leq \overline{C_{th}}. \quad (16)$$

- **Maximum spectrum leasing constraint:** the part of the leased spectrum to be exploited by SN is below the fraction allowed by the PN after solving its problem:

$$0 \leq \beta_{s,j} \leq \beta_{p,j}, \forall j = 1, \cdots, N_{\mathrm{BS}}. \quad (17)$$

In the next sections, we investigate two approaches to solve the PN/SN collaboration. A disjoint approach where the PN starts by optimizing its corresponding variables to maximize its profit while respecting the CO_2 emissions and QoS constraints is investigated in Section IV. In the decentralized approach, the SN considers the parameters obtained from PN and determines the fractions of bandwidth to be leased in order to maximize its profit as well. Consequently, the PN optimization needs to be solved rapidly, i.e., in real-time in order to allow the SN to optimize its parameters. Hence, we need to employ a fast and low-complex algorithm that target the maximum profit with a relatively high accuracy. The second approach, described in Section V, jointly optimizes a utility function based on the profits of both networks: PN and SN. In this case, more exchange of information is required between both networks to determine the best solution for the cognitive collaboration.

IV. Disjoint Profit Maximization

In the distributed profit maximization scenario, the PN maximizes its profit with respect to a PN CO_2 emissions constraint limited by a fraction of the total allowed CO_2 emissions in the geographical area. Then, PN provides its optimized parameters to the SN that optimizes its profit given the SN. However, the SN CO_2 emissions constraint defined by a fraction $1 - \alpha$. In other words, $C_{th} = \alpha\overline{CO_2}$ and $\overline{C_{th}} = (1-\alpha)\overline{CO_2}$. The advantage of this disjoint approach is that the PN management is not affected by the SN activity but rather by α. In addition, the disjoint approach does not require a third party, e.g., a broker, since the PN and SN management are performed successively not simultaneously.

A. PN Profit Maximization

1) Problem Formulation: The PN's optimization problem can be formulated as follows:

$$\underset{\epsilon_{p,j},\beta_{p,j},N_{p,j}^{(\mathrm{roamed})}}{\text{maximize}} \quad \Pi_p, \quad (18)$$

$$\textbf{Subject to:} \quad (9), (10), (11),$$
$$\epsilon_{p,j} \in \{0,1\}, 0 \leq \beta_{p,j} \leq 1,$$

The objective of the PN is to determine which BS should be switched off in order to achieve the maximal profit while satisfying the constraints. The PN problem defined in (18) is a combinatorial problem which is a non-deterministic polynomial-time hard (NP-hard) problem due to the existence of the binary variables $\epsilon_{p,j}$, $j = 1, \ldots, N_{\mathrm{BS}}$ [36]. That is, the optimal solution can only be found using high-complexity ES method and cannot be determined analytically. In this section, we propose a low complexity algorithm that achieves a relatively high PN profit close to the one obtained by ES as it will be shown in the numerical results.

2) Proposed PN Algorithm: The PN is required to optimally manage the spectrum and its BSs in order to reach the maximum profit. The spectrum management involves the spectrum leasing and/or sharing operation during the collaboration with the SN. The BS management decides whether to activate or deactivate the BSs depending on their loads and the total PN CO_2 emissions. Intuitively, the BS that should be deactivated is the one that pollutes the most and presents the lowest profit when active. Hence, we define a metric called profit per CO_2 emissions ($\$/Kg$) defined as the ratio of the profit of a given active BS over its corresponding CO_2 emissions. We propose an algorithm to switch off the BSs that either have lower profit per CO_2 emissions or infringe the CO_2 emissions constraint.

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We first compute the profit of the two extreme cases when all the BSs are active, denoted by "All active", and all the BSs are inactive denoted by "All inactive". Note that in the "All active" or "All inactive" scenarios, the parameters $\beta_{p,j}, N_{p,j}^{(\text{roamed})}$ can be determined, for $j = 1, \ldots, N_{\text{BS}}$, as

- if $\epsilon_{p,j} = 1$, then $$\begin{cases} \beta_{p,j} = 1 - \sum_{\sigma}^{\Sigma_p} \frac{w_{p,j}^{(\sigma)} N_{p,j}^{\sigma}}{W}, \\ N_{p,j}^{(\text{roamed})} = 0, \end{cases} \quad (19)$$
- if $\epsilon_{p,j} = 0$, then $$\begin{cases} \beta_{p,j} = 1, \\ N_{p,j}^{(\text{roamed})} = \min\{\overline{N}_s, N_{p,j}\}. \end{cases} \quad (20)$$

However, respecting the SN service capacity, the outage rate, and the CO_2 emissions constraints is not always guaranteed for any combination of $\boldsymbol{\epsilon_p}$. Hence, we propose to start by switching off all the BSs that, when they are inactive, provide a profit higher than when they are active. The reason behind this choice is that, by switching off these BSs, we gain profit and reduce CO_2 emissions, simultaneously. However, we need to ensure that the service outage is not affected, i.e., equations (9) and (10) are satisfied. At this stage, i.e., after switching off all the BSs with inactive profit higher than active profit, if the outage and roamed users constraints are not violated, the optimal solution with respect to $\boldsymbol{\epsilon_p}$ is already reached. Otherwise, we need to switch off additional BSs till respecting all the constraints. However, the BS to be switched off needs to be smartly chosen and hence, corresponds to the BS with the lowest profit per CO_2 emissions. The proposed network and spectrum management scheme are summarized in **Algorithm 1**.

Algorithm 1 PN BSs Management based on minimum active profit per CO_2 emissions metric

1: Initialize $\boldsymbol{\epsilon}_p = [1, \cdots, 1]$, (i.e., all the PN BSs are active).
2: Compute the profits of each BS in the *active* and *inactive* states using (8).
3: Switch off all BS with *inactive* profit higher than *active* profit such as (9) is respected.
4: Compute the new total PN profit, Π_p using (8), the new service outage using (10), and the new PN total CO_2 emissions $\mathcal{F}_p^{CO_2}$ using (11).
5: **while** ($\mathcal{F}_p^{CO_2} \geq C_{th}$) **do**
6: Switch off the PN BS with lowest active profit per CO_2 emissions, and which its elimination does not violate the QoS constraint (equation 10). Denote its index by $\hat{j}$ and update $\boldsymbol{\epsilon}_p$.
7: Set $\beta_{p,\hat{j}} = 1$ and $N_{p,\hat{j}}^{(\text{roamed})} = N_{p,\hat{j}}$.
8: Update Π_p, $\mathcal{F}_p^{CO_2}$, and the new service outage.
9: **end while**
10: The maximum profit is given by the last value of Π_p using the resulted $\boldsymbol{\epsilon}_p$.

Note that this low complexity approach aims to achieve a sub-optimal solution in terms of total profits by optimizing the BS statuses $\boldsymbol{\epsilon}_p$. The achieved solution respects all considered constraints in the PN optimization problem without overloading the SN BSs. In addition, **Algorithm 1** requires at most N_{BS} iterations whereas the exhaustive search needs $2^{N_{BS}}$ tests to reach the optimal solution.

B. SN Profit Maximization

1) Problem Formulation: After solving the PN optimization problem (18), the SN aims to maximize its profit given the PN outputs. The SN optimization problem is given as follows

$$\underset{\epsilon_{s,j}, \beta_{s,j}, N_{s,j}}{\text{maximize}} \ \Pi_s \quad (21)$$
Subject to: (13), (14), (15), (16), (17).

As mentioned previously, the SN does not have a service outage constraint for its users. Hence, the case where the roamed users are equal to the SN service capacity $\overline{N_s}$ is possible since it may provide higher profit to the SN with a roaming profit greater than the profit of serving SN users.

2) Proposed SN Algorithm: Once $\boldsymbol{\epsilon_p}$ and $\beta_{p,j}$ are determined, the SN can determine the required $\beta_{s,j}$ that maximizes its profit after serving the PN roamed users. The objective of the SN is to achieve a tradeoff between the reduction of the spectrum sharing and/or leasing cost and the increase in the number of secondary users to be served in order to increase the service profit. At the same time, $\beta_{s,j}$ needs to be computed such that (4) and (14) are respected. Note here that the spectrum sharing secondary users might require a higher bandwidth fraction than the spectrum leasing users due to the interference constraint. Hence, spectrum leasing might be more beneficial to the SN if its cost is lower than the spectrum sharing. In the case where the SN does not meet the CO_2 constraint, it is forced to switch off some BSs till meeting the CO_2 transmission threshold $\overline{C_{th}}$. The SN BSs that are eligible to be switched off are those that correspond to the active PN BSs. In fact, when a PN BS is off, the corresponding SN BS is expected to serve the roamed users and cannot be switched off. From another side, the BSs with SN lowest profit per CO_2 emissions are the first to be switched off. We repeat this procedure until meeting the CO_2 constraints. **Algorithm 2** summarizes the switching off procedure of the SN BSs.

Algorithm 2 SN BSs Management in distributed profit maximization

1: Define $\mathcal{B}$ as set of SN BS_j where the PN BS_j are on, i.e., $\epsilon_{s,j} = 1$.
2: Compute the SN total CO_2 emissions, $\mathcal{F}_s^{CO_2}$ using (16).
3: **while** ($\mathcal{F}_s^{CO_2} \geq \overline{C_{th}}$) **do**
4: Switch off the SN BS with lowest active profit per CO_2 emissions that belongs to $\mathcal{B}$ and denote by $\hat{j}$ its index.
5: Set $\beta_{p,\hat{j}} = 0$.
6: Update Π_s and $\mathcal{F}_s^{CO_2}$.
7: **end while**
8: The maximum profit is given by the last value of Π_s using the resulted $\boldsymbol{\epsilon}_s$.

V. Joint Profit Maximization

In this Section, maximizing the PN and the SN profits is performed simultaneously through a unique optimization

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problem. This is the case in which the optimization problem is solved by a third party, i.e., a broker, that provides the best solutions, the corresponding performances, and profits to both PN and SN. If a mutual agreement is reached between the PN and SN, the obtained joint solution will be adopted.

A. Problem Formulation

In the joint profit maximization, the objective is to maximize a weighted sum of the PN and SN profits that we define as, sum of weighted profits (SWP) metric, subject to constraints of both networks.
The objective function is the SWP, denoted by $\Pi_{ps}(\theta)$, and is given by:

$$\Pi_{ps}(\theta) = \theta\ \Pi_p + (1-\theta)\ \Pi_s, \tag{22}$$

where θ is a weight coefficient ($0 \leq \theta \leq 1$) of the PN and the profits Π_p and Π_s are the functions defined in (8) and (12), respectively. The corresponding constraints of this problem include the constraints of the distributed problems in the previous Section. However, some of the constraints, such as the PN and SN CO_2 emissions constraints, are combined in one constraint giving more flexibility to both networks in their on/off switching decisions. For instance, the total CO_2 emissions, denoted by $\mathcal{F}^{CO_2}$, has to be less than the total allowed CO_2 emissions threshold as given below:

$$\mathcal{F}^{CO_2} = \mathcal{F}_p^{CO_2} + \mathcal{F}_s^{CO_2} \leq \overline{CO_2}. \tag{23}$$

In addition, the roamed users constraint in (9) and the service capacity constraint in (15) are combined in the following constraint:

$$0 \leq N_{s,j} + N_{p,j}^{(\text{roamed})} \leq \overline{N}_s, \forall j = 1, \cdots, N_{\text{BS}}. \tag{24}$$

Note that, in (9) and (15), the decision variables are only $N_{p,j}^{(\text{roamed})}$ and $N_{s,j}$, respectively. However, in (24), both of them are considered as decision variables, but due to the existence of constraint (10), the service priority is given to PN users. From another side, the fraction of the spectrum leasing for the PN and SN will be the same, i.e., $\beta_{s,j} = \beta_{p,j} = \beta_{ps,j}$. We define the 2-by-$N_{\text{BS}}$ matrix $\boldsymbol{\epsilon}_{ps}$ describing the status (on or off) of each BS. The two rows of $\boldsymbol{\epsilon}_{ps}$ correspond to the PN and SN BSs, respectively. The columns correspond to the different cells. Note that at least one BS should be active in each cell to guarantee the PN QoS. That is, the columns of $\boldsymbol{\epsilon}_{ps}$ belong to the set of possible cell states, denoted by $\mathcal{S}$, where

$$\mathcal{S} = \left\{\mathcal{S}1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \mathcal{S}2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \mathcal{S}3 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}\right\}.$$

Note that the parameters $\beta_{ps,j}, N_{p,j}^{(\text{roamed})}$ of the cell j can be determined for each state such as

- if $\epsilon_{ps,j} = \mathcal{S}1$, then $\begin{cases} \beta_{ps,j} = 1, \\ N_{p,j}^{(\text{roamed})} = \min\{\overline{N}_s, N_{p,j}\}, \end{cases}$ (25)
- if $\epsilon_{ps,j} = \mathcal{S}2$, then $\begin{cases} \beta_{ps,j} = 0, \\ N_{p,j}^{(\text{roamed})} = 0, \end{cases}$ (26)
- if $\epsilon_{ps,j} = \mathcal{S}3$, then $\begin{cases} \beta_{ps,j} = 1 - \sum_{\sigma}^{\Sigma_p} \frac{w_{p,j}^{(\sigma)} N_{p,j}^{\sigma}}{W}, \\ N_{p,j}^{(\text{roamed})} = 0. \end{cases}$ (27)

The joint profit maximization problem is given as follows:

$$\underset{\epsilon_{ps,j}, \beta_{ps,j}, N_{p,j}^{(\text{roamed},\sigma)}, N_{s,j}}{\text{maximize}} \quad \Pi_{ps}, \tag{28}$$

$$\textbf{Subject to:} \quad (10), (13), (14), (23), (24),$$
$$\epsilon_{ps,j} \in \mathcal{S}, \quad 0 \leq \beta_{ps,j} \leq 1. \tag{29}$$

B. Proposed Algorithm for Joint Profit Maximization

Note that the problem (28)-(29) is a combinatorial optimization problem with up to $4^{N_{\text{BS}}}$ possible cases. In order to solve this combinatorial problem, we define the SWP per CO_2 emissions metric as $\frac{SWP}{\mathcal{F}^{CO_2}}$. We, then, proceed by an iterative algorithm to solve the centralized profit maximization problem. We start by computing the partial SWP of each cell state which is stored in a 3-by-N_{BS} matrix. Since the objective is to maximize the global SWP Π_{ps}, we select the state providing the maximum partial SWP at each cell. Note that after this choice, if the CO_2 constraint, (23), is respected, the solution of the problem is already found. However, this is not always the case since the state corresponding to the higher partial SWP usually corresponds to active PN and SN BSs which is the state with highest CO_2 emissions as well. Consequently, if the constraint (23) is not respected, we search for the cell with lowest $\frac{SWP}{\mathcal{F}^{CO_2}}$ and switch it to the state with lowest CO_2 emissions and this cell is excluded from next iterations. We repeat this procedure for the rest of the cells till respecting the constraint (23).

The algorithm is summarized in **Algorithm 3**. Notice that it requires at most N_{BS} iterations whereas the ES requires $4^{N_{\text{BS}}}$ iterations.

VI. Numerical Results

In the numerical results, we consider a PN and SN composed of 12 BSs each. We present the different values of the parameters and prices in Table I [35]. We denote by the \$ the monetary unit.

In Fig. 2, we start by investigating the decentralized approach. We plot the PN and SN profits for the ES and the proposed algorithm as a function of the fraction of PN CO_2 emissions, α. We also plot the total profit computed as the sum of the PN and the SN profits. The aim is to highlight the effect of the CO_2 emissions constraint on the management of both networks. We first note that the proposed algorithm presents about $90\% - 100\%$ of the ES profit which is considered to be

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Algorithm 3 PN and SN Joint Profit Maximization

Compute the SWP of each state in all cells.
Switch to the state having the highest SWP in each cell.
Compute the new SWP, the new $\mathcal{F}^{\mathrm{CO_2}}$ using (23), and the new service outage using (10).
while $(\mathcal{F}^{\mathrm{CO_2}} \geq \overline{\mathrm{CO_2}})$ **do**
  Find the cell with lowest $\frac{\mathrm{SWP}}{\mathcal{F}^{\mathrm{CO_2}}}$, and denote by $\hat{j}$ its index.
  Switch to the state, in the cell $\hat{j}$, having the lowest CO_2 emissions and which does not violate the QoS constraint (equation 10).
  Update ϵ_{ps}.
  Set $\beta_{ps,\hat{j}}$ and $N_{p,\hat{j}}^{(\mathrm{roamed})}$ using (25)-(27).
  Update Π_{ps}, $\mathcal{F}^{\mathrm{CO_2}}$, and the new service outage.
end while
The maximum profits are given by the last values of Π_{ps} using the resulted ϵ_{ps}.

TABLE I: Network parameters and prices

Parameter	Value	Parameter	Value
Number of BSs N_{BS}	12	Cell radius (m)	500
Total bandwidth W (MHz)	55	Allowed outage P_{out}	5%
Sharing price p_{ss}($/MHz)	100	Leasing price p_{sl}($/MHz)	120
Service Capacity $\overline{C}_i$	50	Interf. threshold I_{th} (dB)	0
Service prices $p_{\mathrm{op},i}^{(\sigma)}$($)	4	Roaming price p_{roam}($)	4.25
Received power $P_{\mathrm{min}}^{(\sigma)}$ (dBm)	-90	Rate per user $r_i^{(\sigma)}$ (kbps)	250
Pollutant coefficients ϕ_p, ϕ_s	0.01	Pathloss constant K (dB)	-128.5
Pollutant coefficients ψ_p, ψ_s	0.1	Pathloss exponent ν	3.76
Scaling parameter a_i	7.84	BS constant power b_i (W)	71.5
CO_2 emissions fraction α	0.4	CO_2 threshold $\overline{\mathrm{CO_2}}$ (Kg)	5152

high efficient. We also show that the SN profit, corresponding to the proposed algorithm, is most of the time higher than the ES profit which means that the profit loss in the PN is compensated in the SN profit. This minor loss compared to the ES is mainly caused by the fact of switching on PN BSs with lower CO_2 emissions which allows the SN to emit more

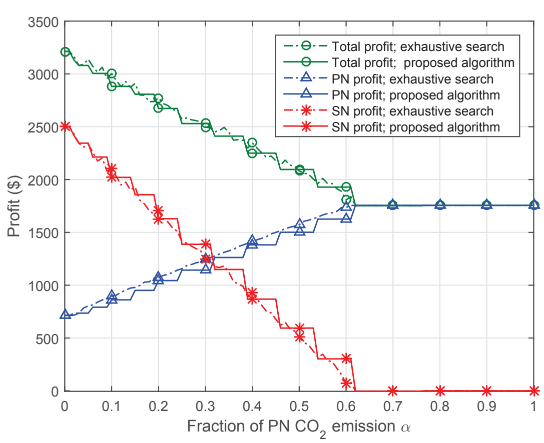

Fig. 2: PN and SN profits maximization using the ES and low complexity algorithms for the decentralized approach vs. the fraction of CO_2 emissions α.

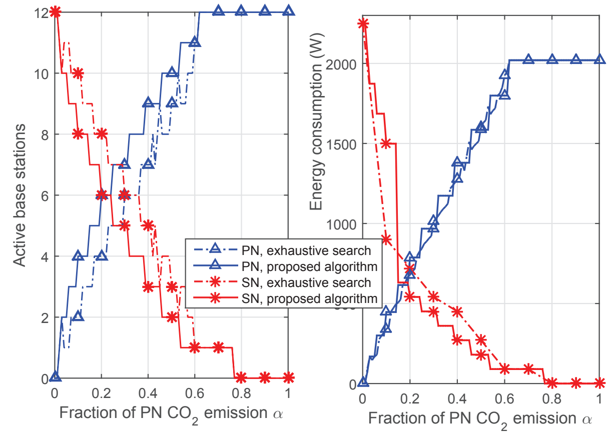

Fig. 3: PN and SN energy consumption and active BSs using the ES and low complexity algorithms for the decentralized approach vs. the fraction of CO_2 emissions α.

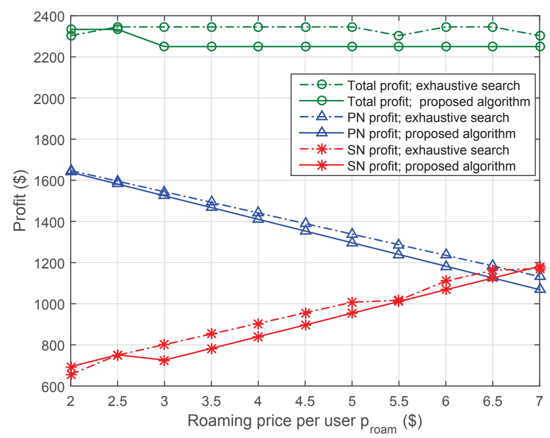

Fig. 4: PN and SN profits using the ES and low complexity algorithms for the decentralized approach vs. the roaming price p_{roam}.

CO_2 by serving more users. Although we are optimizing the PN profit before the SN profit, this compensation in profits is visible in the sum profit in which the proposed algorithm and the ES are very close. In addition, we notice that the profit of the proposed algorithm is increasing and piece-wise constant.

To explain this fact, we plot, in Fig. 3, the PN energy consumption and active BSs as a function of α. As shown in Fig. 3, the proposed on/off switching scheme sort the BSs according to their profit per CO_2 emissions. Consequently, when α increases the next BS in the ranking will be switched on if it respects the constraints. In addition, we notice that there is a strong correlation between the variation of the number of active BSs and the energy consumption for both PN and SN.

In Fig. 4, we plot the profits of the PN and the SN as a function of the roaming price, p_{roam}. We notice that both profits highly depend on p_{roam} where the PN and SN profits are decreasing and increasing functions of p_{roam}, respectively. In addition, we notice that there is a certain value of p_{roam}, around 6.5$, that ensures equal profits of both networks, which means

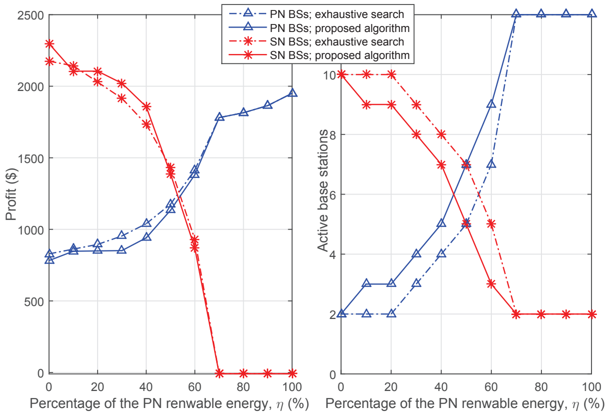

Fig. 5: PN and SN profits using the ES and low complexity algorithms for the decentralized approach vs. the renewable energy availability parameter η.

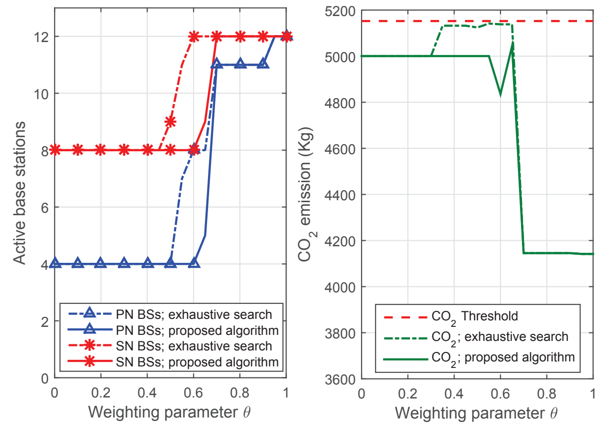

Fig. 7: PN and SN active BSs and the total CO_2 emissions using the ES and low complexity algorithms for the centralized approach vs. the weighting parameter θ.

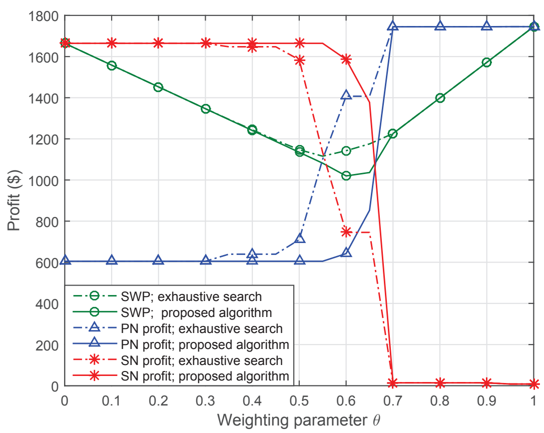

Fig. 6: PN and SN profits using the ES and low complexity algorithms for the centralized approach vs. the weighting parameter θ.

that p_{roam} can be used to regulate the market when needed.

In Fig. 5, we highlight the effect of the renewable energy availability on the PN and SN profits by evaluating them in addition to the number of active BSs versus a parameter η denoting the percentage of renewable energy available at the PN BS sites. This percentage is defined for the entire PN as $\eta = \sum_j \frac{\mathcal{E}_j^{(g)}}{\mathcal{E}_j}$. Fig. 5 shows that the increase of η encourages the PN to switch on more BSs given the same fraction of CO_2 emissions, selected to be $\alpha = 0.4$. This activation corresponds to a profit increase in a quadratic slope up to $\eta = 70\%$ where all the BSs are on, despite $\alpha = 0.4$. This increase is mainly due to the reduction of roaming expenses and the increase of the fraction of leased spectrum. After 70%, the increase of the profit has a slower slope since the profit becomes only dependent on the reduction of the energy price related to the dynamic pricing in (6). Hence, the local deployment of renewable energy sources generates higher profits in addition to being an environmentally friendly decision.

In the sequel, we focus on the performance of the collaboration scheme using the centralized approach. In Fig. 6, we investigate the joint profit maximization by plotting the corresponding PN and SN profits as well as SWP as a function of θ. We show that **Algorithm 3** based on the ratio of the SWP over the CO_2 emissions gives results matching the ES at high and low values of θ. That is, **Algorithm 3** gives optimal results when one network has high priority in the profit maximization compared to the other. Nevertheless, in the range where $0.5 < \theta < 0.7$ the profit of **Algorithm 3** achieves at least 88% of the ES profits. Note, regardless of the value of θ, the PN QoS is always maintained. In addition, we notice that there is a stagnation level in which the PN and SN profits are constants as θ increases. However, when θ exceeds 0.5, the SN profit presents a huge decrease to zero while the PN profit increases by two folds.

In Fig. 7, we plot the number of active BSs and the total CO_2 emissions caused by both networks as a function of θ to explain the stagnation in Fig. 6. We notice that, when θ is low (i.e., the priority is to maximize the SN profit), the majority of the PN BSs are switched off. The reason is that the roamed PN users contribute in increasing the SN profit thanks to the imposed roaming service cost. In addition, it provides more bandwidth to serve both SN and PN roamed users. Afterward, when θ exceeds 0.6, the PN starts to switch on the rest of its BSs which suddenly increases its profit and decrease the SN profit as shown in Fig. 6. Unlike the disjoint profits maximization which involves opposite BSs activation behavior between the PN and SN, the BSs activation here increases with θ for both PN and SN. Also, we notice that in the interval in which Algorithm 3 is lower than the ES, the CO_2 emissions are also lower than the ES.

VII. Conclusion

In this paper, we investigated an environment-aware framework for cognitive radio cellular networks. The primary and secondary networks (PN and SN) collaborate together in order to maximize their own profits while meeting the PN QoS and the total CO_2 emissions constraint imposed by the regulator.

In the collaboration scheme, PN switches off some of its base stations (BSs) to reduce its carbon footprint then offloads the corresponding users to the SN's BSs. In return, the SN serves these PN roamed users and freely exploit the spectrum. Low complexity profit maximization algorithms for decentralized and centralized optimization approaches are proposed. The spectrum is dynamically managed between the PN and SN either by sharing or leasing depending on the statuses of the PN's BSs which are determined based on a metric named profit per CO_2 emissions. In the numerical results, we show that for both decentralized and centralized cases, these algorithms achieve close performance to those obtained with the high-complexity exhaustive search method. Moreover, we show that the renewable energy availability and the roaming cost are important parameters affecting the networks' profits. They can be exploited to regulate the market.

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