Green Downlink Radio Management Based Cognitive Radio LTE HetNets

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***Abstract*—In this paper, the problem of radio and power resource management in underlay cognitive radio heterogeneous networks is investigated, where macro and pico Base Stations (BSs) are considered as primary BSs while femto BSs are considered as secondary BSs. The goal is to minimize the total primary power consumption and maximize the secondary utility of the network while satisfying the primary user quality of service determined by target data rate and interference constraints. Furthermore, a green communication algorithm is implemented based on a sleeping strategy. Simulations study investigates the performance of the proposed scheme and shows an important saving in terms of total power consumption.**

***Index Terms*—Cognitive radio, heterogeneous networks, sleeping strategy.**

I. Introduction

Green communications and energy efficiency in wireless communication networks has attracted the interest of researchers recently [1]. In fact, downlink communication in cellular networks accounts for over 70% of the total energy consumption in the network [2]. Several schemes were proposed to save the energy consumption using dynamic Base Stations (BSs) switching-on/off saving strategies. The proposed schemes in the literature tried to reduce the downlink power consumption by switching off BSs during their off-peak hours when data traffic is low [3]. The work presented by Koudouridis *et. al* in [4] proposed a simulated annealing-based algorithm to turn on-off BSs in a Heterogeneous Networks (HetNets). The authors in [5] introduced two node switching modes which operate on an intermediate and fast time scale in order to exploit short/long idle periods of the BSs. Two heuristic switching ON/OFF approaches were proposed in [6], where equal power distribution is considered.

Since most of the wireless data traffic takes place in indoor environments, mobile users may have difficulty in receiving high data rates from Macrocell Base Stations (MBSs) due to the penetration loss. Smallcell technology, including Pico Base Stations (PBSs) and Femto Base Stations (FBSs), which is short range and low cost is designed to handle the high amount of traffic with a low power consumption. However, all aforementioned green techniques did not consider cross-interference in their system model. In addition to that they are limited to the sleeping strategies without optimizing neither the transmitted power nor the resource allocation.

On the other hand, Cognitive Radio (CR) has been proposed recently to solve the spectrum scarcity problem. The concept of the CR is that the secondary users are allowed to allocate some primary spectrum opportunistically [7]. Few schemes in the literature combine the CR concept with HetNets by considering the FBSs and their corresponding users as a secondary network [8], [9]. For instance, the work in [8] assumed overlay CR, where the primary users may release some bandwidth for the secondary transmission. Thus, the interference between primary and secondary networks is negligible. In [9], the authors assumed underlay CR, where secondary users access the spectrum simultaneously with the primary users under some interference limitation constraints to maintain a certain Quality-of-Service (QoS) of the primary transmission, and they proposed an iterative algorithm to solve the resource allocation problem for the uplink transmission.

However, to the best of the authors knowledge, the downlink problem of primary and secondary resource and power management for HetNets including primary BSs employing sleeping strategy and secondary BSs has not been discussed so far, which is what we address in this paper. Therefore, our contributions in this paper can be summarized as follows: (i) Formulating a downlink optimization problem for CR-HetNets that aims to minimize the total primary power consumption of the network and maximize the secondary rate utility, taking into account the BSs power budget, the QoS for each primary user, and the interference between primary and secondary BSs; (ii) Implementing a green communication algorithm for primary BSs based on a sleeping strategy; (iii) Proposing a two step allocation computationally efficient procedure for resource allocation; and (iv) Deriving closed form expressions for the primary and secondary BSs power where three different secondary utility functions are considered depending on the level of fairness among the secondary users.

The reminder of the paper is organized as follows. Section II investigates the CR-HetNets system model. The primary problem formulation and solution is given in Section III. Section IV gives the secondary problem formulation and solution. The numerical results are discussed in Section V. Finally, the paper is concluded in Section VI.

II. System Model

We consider a cognitive Long-Term Evolution (LTE) CR-HetNets system model, where the secondary FBSs share the spectrum with the primary MBSs and PBSs. The geographical area of interest is subdivided to M hexagonal cells of equal sizes. It is assumed that at each hexagonal cell, m, one MBS is placed in the center of cell and L_m PBSs are distributed at the edges as shown in Fig. 1. Also, we assume F_m FBSs are distributed uniformly inside the cell m. Let us define the total number of primary and secondary users as U_{tot} and K_{tot}, respectively, where $U_{\text{tot}} = \sum_{m=1}^{M} U_m$ and $K_{\text{tot}} = \sum_{m=1}^{M} K_m$. U_m and K_m are the number of primary and secondary users per cell m, respectively.

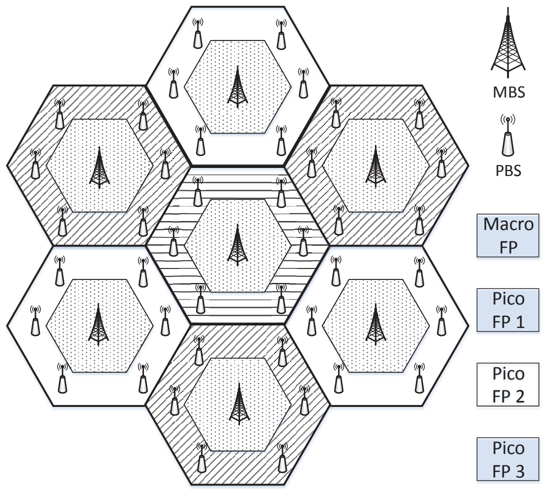

Fig. 1: Primary heterogeneous network.

In LTE, orthogonal frequency division multiple access (OFDMA) is the access scheme for the downlink. The available spectrum is divided into Resource Blocks (RBs) consisting of 12 adjacent subcarriers. Each RB has a bandwidth of $B_{\rm RB} = 180$ KHz while each subcarrier has a bandwidth of 15 KHz [10]. We denote by $N_{\rm RB}^{\rm (BS)}$ the number of available RBs at the BS. It is assumed that each FBS is equipped with two transceivers: one for primary spectrum sensing to detect the spectrum holes in order to utilize them and the other transceiver is for the cognitive data communication. Hence, FBSs use the latter transceiver for underlay cognitive transmission. Finally, we make the following assumptions: (i) A user is served by at most one BS (either MBS, PBS, or FBS) with a unique RB. (ii) Using the Frequency Partitions (FP) technique shown in Fig. 1, there is no inter-tier interference on the downlinks of MBSs and PBSs as they are using different sets of orthogonal RBs. (iii) The remaining interference can be categorize as: 1) inter-tier interference between secondary BSs and primary BSs that are using the same sets of RBs; 2) intra-tier interference between PBSs and neighboring PBSs that are in the same cell and using the same sets of RBs. As will be shown in the sequel, the former interference can be solved by respecting a certain primary interference threshold I_{th} [11]. The latter interference issue can be solved using resource allocation algorithm. In our framework, we assume that the primary and secondary problem are solved for different phases and repeated every time slot. Also, it is assumed that the channel gains are constant during the coherence time.

A. Pathloss and Channel Model

Different pathloss models are employed in our system model and given as follows (assuming that all the distances in this paper are given in meters) [12]

1) Indoor-indoor pathloss: The pathloss in dB between an indoor user and its serving FBS is given by $\mathrm{PL} = 38.46 + 20\log_{10} d_{\rm in-in} + 0.3 d_{\rm in-in}$, where $d_{\rm in-in}$ is the indoor distance between indoor user and its corresponding FBS.

2) Outdoor-indoor pathloss: The pathloss in dB between an outdoor user and its FBS is given by $\mathrm{PL} = \max(15.3 + 37.6\log_{10} d_{\rm ou-in}, 38.46 + 20\log_{10} d_{\rm in-in} + 0.3 d_{\rm in} + L_{\rm ow})$, where $d_{\rm ou-in}$ is the distance traveled outdoor between the outdoor user and the building external wall, $d_{\rm in}$ is the indoor traveled distance between the building wall and FBS, and $L_{\rm ow}$ is an outdoor-indoor penetration loss.

3) Outdoor-outdoor pathloss: The pathloss in dB between an outdoor user and its MBS or PBS is given by $\mathrm{PL} = 15.3 + 37.6\log_{10} d_{\rm ou-ou}$, where $d_{\rm ou-ou}$ is the outdoor distance between the outdoor user and its corresponding MBS or PBS.

4) Indoor-outdoor-indoor pathloss: The pathloss in dB between an indoor user and a FBS that is not serving it is given by $\mathrm{PL} = \max(15.3 + 37.6\log_{10} d_{\rm ou-in}, 38.46 + 20\log_{10} d_{\rm in-in} + 0.3 d_{\rm in} + L_{\rm ow} + 0.3 d_{\rm in,1} + 0.3 d_{\rm in,2} + 2L_{\rm ow})$, where $d_{{\rm in}_f}$ is the indoor traveled distance between the building wall and FBS f.

The channel gain, which is the ration between the user u and the BS over RB n, can be expressed as:

$$h_{n,{\rm BS},u} = 10^{\frac{-PL_{{\rm BS},u} - \xi_{{\rm BS},u} + 10\log_{10} F_{n,{\rm BS},u}}{10}}, \tag{1}$$

where $\xi_{{\rm BS},u}$ captures log-normal shadowing with zero-mean and a standard deviation σ_ξ. $F_{n,{\rm BS},u}$ corresponds to Rayleigh fading power between user u and the BS over RB n, with a Rayleigh parameter a such that $E\{|a|^2\} = 1$. Fast Rayleigh fading is assumed to be approximately constant over the subcarriers of a given RB, and independent identically distributed over RBs.

B. Base Station Power Model

We consider that only MBSs and PBSs can be set in active or sleep mode. While FBSs are always considered to be in the active mode. In the active mode, the BS is serving a certain number of users connected to the network. The power consumption of a BS corresponding to this mode, noted $P_{\rm BS}$, can be computed as follows:

$$P_{\rm BS} = a_{\rm BS} P_{\rm BS}^{\rm tx} + b_{\rm BS}, \tag{2}$$

where $a_{\rm BS}$ corresponds to the power consumption that scales with the radiated power due to amplifier and feeder losses and $b_{\rm BS}$ models an offset of site power which is consumed independently of the average transmit power and is due to signal processing, battery backup, and cooling. In (2), $P_{\rm BS}^{\rm tx} = \sum_{n=1}^{N_{\rm RB}^{\rm (BS)}} P_{n,{\rm BS}}$, denotes the radiated power of the BS, which corresponds to the sum of the radiated power over the RBs $P_{n,{\rm BS}}, n = 1, \cdots, N_{\rm RB}^{\rm (BS)}$ and depends on the RB state. The value of $P_{n,{\rm BS}}$ greater than 0 if RB n of the BS is allocated to a certain user and 0 otherwise. Note that $a_{\rm BS}$ and $b_{\rm BS}$ differ from one BS to another depending on the type of the BS.

III. Primary Problem Formulation and Solution

We assume that the primary BS forces the received cross-tier interference to not exceed a fixed interference threshold. Therefore, the achievable data rate of user u served by a primary BS over RB n in cell m can be given as

$$R_{n,j,u}^m = B_{\rm RB} \log_2(1 + \mathrm{SINR}_{n,j,u}^m), \tag{3}$$

where $\text{SINR}^m_{n,j,u}$ is signal-to-interference-plus-noise-ratio and is given by $\text{SINR}^m_{n,j,u} = \frac{\epsilon^m_{n,j,u} P^m_{n,j} h_{n,j,u}}{I_{th}+\mathcal{N}_0}$. $P^m_{n,j}$ is the primary BS j transmitted power allocated to RB n in cell m, while $\epsilon^m_{n,j,u}$ is a binary variable that is equal to 1 if primary user u is allocated the RB n of BS j in cell m and 0 otherwise. $\mathcal{N}_0 = \mathcal{N} B_{\text{RB}}$ is the background noise power, where $\mathcal{N}$ is the noise power density. The rate in (3) is considered to be the worst case scenario or a lower bound of the primary rate as the interference threshold, I_{th}, may not be reached by the secondary BSs. Consequently, the actual primary user achieved rate is greater or equal to this lower bound and it is mainly derived by considering the actual secondary interference instead of I_{th}. Therefore, our optimization problem OP 1 that aims to minimize the total power consumption using the sleeping strategy, while satisfying a certain primary QoS is formulated as follows

$$\text{OP 1:} \underset{\boldsymbol{\pi},\boldsymbol{\epsilon},\boldsymbol{P}\geq 0}{\text{minimize}} \quad \sum_{m=1}^{M}\sum_{j=0}^{L_m}\pi^m_j\left(a^m_j\sum_{u=1}^{U_m}\sum_{n=1}^{N_{\text{RB}}^{(j)}}\epsilon^m_{n,j,u}P^m_{n,j}+b^m_j\right)$$

subject to: (4)

$$\sum_{u=1}^{U_m}\sum_{n=1}^{N_{\text{RB}}^{(j)}}\epsilon^m_{n,j,u}P^m_{n,j}\leq \bar{P}_j, \quad \forall m=1,..,M,\forall j=0,..,L, \quad (5)$$

$$\sum_{j=0}^{L}\sum_{n=1}^{N_{\text{RB}}^{(j)}}R^m_{n,j,u}\geq R_{th}, \quad \forall u=1,..,U_m,\forall m=1,..,M, \quad (6)$$

$$\sum_{u=1}^{U_m}\epsilon^m_{n,j,u}\leq 1, \quad \forall m=1,..,M,\forall j=0,..,L,\forall n=1,..,N_{\text{RB}}^{(j)}, \quad (7)$$

where (5) and (6) represent the primary peak power and primary minimum user rate constraints, respectively. Equation (7) ensures that each primary user is served by at most one BS with a unique RB. Note that index j represents the MBS if $j=0$ and the PBS otherwise. π^m_j is a binary variable that is equal to 0 if the BS j in cell m is turned off; otherwise, $\pi^m_j = 1$. The formulated OP 1 given in (4)-(7) is a non-convex problem and considered as NP-hard problem due to the existence of the binary variables, hence, we propose to solve it in three steps. Firstly, we start with a feasible power and switching binary variable vector (i.e., $\boldsymbol{\pi}$) to find the RBs allocation iteratively. We then derive closed-form expressions of the optimal primary powers allocation. Finally, greedy sleeping algorithm is applied.

A. RB Allocation

Given feasible powers and switching binary variables, the RB allocation problem can be solved heuristically in polynomial time since the objective function is monotonically increasing with the SINR. We can find a solution by assigning $\epsilon^m_{n,j,u}(op) = 1$ to user with the maximum $\text{SINR}^m_{n,j,u}$, and $\epsilon^m_{n,j,u}(op) = 0$ for all other users in cell m and eliminate the RB n. This process is repeated for all users and all cells until all primary users assigned to a unique RB n or no more RBs are available. Algorithm 1 summarizes the RB-user allocation at each cell to obtain the optimal $\epsilon^m_{n,j,u}(op)$.

Algorithm 1 RB to User Allocation at Each cell

1: **Initialization:**
Set $\epsilon^m_{n,j,u} = 0, \forall m=1,..,M, \forall j=0,..,L_m, \forall n=1,..,N_{\text{RB}}^{(j)}$.
2: **RB Allocation:**
3: **for** $u=1,\cdots,U_m$ **do**
4: $u(op) = \underset{u}{\text{argmax}}\left(\text{SINR}^m_{n,j,u}\right)$.
5: $\epsilon^m_{n,j,u}(op) = 1$.
6: **end for**

B. Power Allocation

We can solve our convex power optimization problem for fixed binary variables (i.e.,$\boldsymbol{\pi},\boldsymbol{\epsilon}$) by exploiting its strong duality [13] by finding the Lagrangian multipliers that maximize the dual problem as follows

$$\underset{\boldsymbol{\lambda},\boldsymbol{\mu}\geq 0}{\text{maximize}} \quad \underset{\boldsymbol{P}\geq 0}{\text{minimize}} \quad \mathcal{L}(\boldsymbol{\lambda},\boldsymbol{\mu}), \quad (8)$$

where $\mathcal{L}(\boldsymbol{\lambda},\boldsymbol{\mu})$ is the Lagrangian function. $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are Lagrangian vectors that contain the Lagrangian multipliers associated with constraints (5) and (6), respectively. Hence, by solving (8), the optimal power $P^m_{n,j}(op)$ can be given as follows

$$P^m_{n,j}(op) = \left[\frac{\mu^m_u B_{\text{RB}}}{(a^m_j+\lambda^m_j)\ln 2} - \frac{I_{th}+\mathcal{N}_0}{h_{n,j,u}}\right]^+, \quad (9)$$

where $[x]^+ = \max(0,x)$. We can employ the subgradient method to find their optimal values and thus the optimal solution of the problem, see [14] for more details.

C. Sleeping Algorithm

Let us define the total QoS threshold as the ratio between the number of primary users in outage divided by the total number of users for all cells (i.e., $\frac{U_{\text{out}}}{U_{\text{tot}}} \leq \gamma_{\text{out}}$) [6], where γ_{out} denotes the tolerated primary outage threshold. The basic idea of the algorithm is to eliminate redundant MBSs and/or PBSs without affecting the primary QoS. Firstly, at each iteration, the algorithm switches off one primary BS of the total primary BSs in the network and then verify whether the total QoS threshold is satisfied or not. If it is satisfied, the primary BS can be eliminated. Then, the algorithm finds the eliminated BS that provided the lowest total power consumption and eliminate it. This procedure is repeated until no change can be made. The primary resource allocation with sleeping strategy algorithm can be summarized in Algorithm 2.

IV. Secondary Problem Formulation and Solution

Let us assume that the number of femto users are less than or equal to the total number of the available RBs in cell m (i.e., $K_m \leq N_{\text{RB}}^{(m)}$). Thus, the achievable data rate of secondary user k served by FBS f over RB n can be given as

$$R^m_{n,f,k} = B_{\text{RB}}\log_2\left(1+\text{SINR}^m_{n,f,k}\right), \quad (10)$$

where $\text{SINR}^m_{n,f,k} = \frac{\kappa^m_{n,f,k}P^m_{n,f}h^m_{n,f,k}}{\mathcal{I}^m_{n,j}+\mathcal{N}_0}$, $\mathcal{I}^m_{n,j}$ is the cross-tier interference from the primary network to the secondary network and given by $\mathcal{I}^m_{n,j} = \sum_{u=1}^{U_m}\epsilon^m_{n,j,u}(op)P^m_{n,j}(op)h^m_{n,j,u}$. $\kappa^m_{n,f,k}$ is a binary variable that is equal to 1 if secondary user

Algorithm 2 Primary Resource Allocation with Sleeping Strategy Algorithm

1: Initially, all the primary BSs (MBS and PBSs) in all the cells are assumed to be switched on where $\mathcal{S}_0$ contains all primary BSs and L_{tot} is the total number of primary BS in the network.
2: **while** Not converge **do**
3: Apply Algorithm 1 to find the user-RB allocation.
4: Find the optimal power allocation using (9) to calculate the total optimal power P_0 using (4).
5: **end while**
6: Set $\mathcal{S} = \mathcal{S}_0$ $P_{\text{tot}} = P_0$.
7: **for** $l = 1, .., L_{\text{tot}}$ **do**
8: Eliminate BS l from $\mathcal{S}$.
9: Repeat Step 2- Step 5 to find $P_{\text{tot},l}$.
10: **if** $\frac{U_{\text{out}}}{U_{\text{tot}}} \leq \gamma_{\text{out}}$ **then**
11: BS l can be eliminated.
12: **else**
13: BS l can not be eliminated.
14: **end if**
15: **end for**
16: Find the eliminated BS l^* that provided the lowest total power, i.e.,$P_{\text{tot},l^*} = \min(P_{\text{tot},l})$.
17: **if** $P_{\text{tot},l^*} \leq P_{\text{tot}}$ **then**
18: BS l^* is eliminated.
19: $P_{\text{tot}} = P_{\text{tot},l^*}$.
20: $\mathcal{S} \rightarrow \mathcal{S} \backslash \{l^*\}$.
21: **else**
22: No more changes can be made.
23: **end if**
24: The final optimal BS set is $\mathcal{S}$, the final minimum total power is P_{tot}.

k is allocated the RB n of FBS f in cell m and 0 otherwise. Let $\Gamma(R^m_{n,f,k})$ denote the rate utility of the secondary network in cell m. By assuming that FBSs can serve the secondary users only (i.e., working as open mode BSs for secondary users and close mode BSs for primary users), the optimization problem of secondary femtocells that maximize the rate utility while satisfying specific power budget and interference threshold constraints can be divided to parallel optimization problems at each cell m and formulated as

OP 2:

$$\underset{\boldsymbol{\kappa}, \boldsymbol{P}_s \geq 0}{\text{maximize}} \quad \Gamma\left(R^m_{n,f,k}\right) \tag{11}$$

subject to:

$$\sum_{k=1}^{K_m} \sum_{n=1}^{N_{\text{RB}}^{(m)}} \kappa^m_{n,f,k} P^m_{n,f} \leq \bar{P}_f, \quad \forall f = 0, .., F_m, \tag{12}$$

$$\sum_{f=1}^{F_m} \sum_{k=1}^{K_m} \sum_{n=1}^{N_{\text{RB}}^{(m)}} \kappa^m_{n,f,k} P^m_{n,f} \leq \frac{1}{\delta + \sum\limits_{u=1}^{U_m} \epsilon^m_{n,j,u}(op)} I_{th}, \tag{13}$$

$$\sum_{f=1}^{F_m} \kappa^m_{n,f,k} \leq 1, \forall f = 1, .., F_m, \forall n = 1, .., N_{\text{RB}}^{(m)}, \tag{14}$$

where (12) and (13) represent the secondary power budget and cross-tier interference constraints. In (13), the factor $1/\left(\delta + \sum\limits_{u=1}^{U_m} \epsilon^m_{n,j,u}(op)\right)$ is equal to 1 if the RB n is occupied by any primary user, and very high value (i.e., neglected constraint) otherwise, where δ is a very small number. Equation (14) is to ensure that each femto user is served by at most one FBS with a unique RB in cell m.

A. Utility Selection

In this section, we investigate different utility metrics that will be employed in our secondary optimization problem.

Max C/I Utility: The utility of this metric is equivalent to the sum data rate of the cognitive network $\Gamma\left(R^m_{n,f,k}\right) = \sum\limits_{k=1}^{K_m} R^m_{n,f,k}$. This approach is known in the literature as Max C/I [15] as it promotes users with favorable channel and interference conditions by allocating to them most of the resources.

Max-Min Utility: Due to the unfairness of Max C/I resource allocation, the need for more fair utility metrics arises. Max-Min utilities are a family of utility functions attempting to maximize the minimum data rate in the network $\Gamma\left(R^m_{n,f,k}\right) = \min\limits_k (R^m_{n,f,k})$ [16]. By increasing the priority of users having lower rates, Max-Min utilities lead to more fairness in the network. In order to simplify the problem for this approach, we define a new decision variable $R_{\min} = \min\limits_k (R^m_{n,f,k})$. Therefore, our optimization problem becomes

$$\underset{\boldsymbol{\kappa}, \boldsymbol{P}_s, R_{\min} \geq 0}{\text{maximize}} \quad R_{\min} \tag{15}$$

subject to:

$$R^m_{n,f,k} \geq R_{\min} \quad \forall k = 1, ..., K_m, \tag{16}$$

$$(12), (13), (14).$$

Proportional Fair Utility: A tradeoff between the maximization of the sum-rate and the maximization of the minimum rate could be the maximization of the geometric mean data rate $\Gamma\left(R^m_{n,f,k}\right) = (\prod_{k=1}^{K_m} R^m_{n,f,k})^{1/K_m}$ which is equivalent to $\Gamma\left(R^m_{n,f,k}\right) = \sum_{k=1}^{K_m} \ln(R^m_{n,f,k})$ [17]. The proportional fair (PF) metric is fair, since a user with a data rate close to zero will make the whole product go to zero. Hence, any maximization sum-rate algorithm would avoid having any user with very low data rate. In addition to this, the metric will reasonably promote users with good wireless channels (capable of achieving high data rates), since a high data rate will contribute in increasing the product.

B. Secondary Optimization Problem Solution

We can solve our secondary optimization problem in two steps. Firstly find the secondary RB allocation (i.e., find $\boldsymbol{\kappa}$ vector) using Algorithm 1 by applying it to the FBSs. We can then solve our convex optimization problem for fixed $\kappa^m_{n,f,k}$ and iterate until converge. Similar to the primary power allocation, by exploiting the strong duality the secondary power allocation for the Max C/I, Max-Min, PF utilities can be given respectively as

$$P^m_{n,f}(op) = \left[\frac{B_{\text{RB}}}{(\zeta^m_f + \rho^m)\ln 2} - \frac{\mathcal{I}^m_{n,j} + \mathcal{N}_0}{h_{n,f,k}}\right]^+, \tag{17}$$

$$P^m_{n,f}(op) = \left[\frac{\eta_k B_{\text{RB}}}{(\zeta^m_f + \rho^m)\ln 2} - \frac{\mathcal{I}^m_{n,j} + \mathcal{N}_0}{h_{n,f,k}}\right]^+, \tag{18}$$

$$P_{n,f}^{m}(op) = \left(\frac{B_{\text{RB}}}{(\zeta_f^m + \rho^m)\ln 2} \prod_{\substack{q=1\\ q\neq k}}^{K_m} R_{n,f,q}^{m} - \frac{\mathcal{I}_{n,j}^{m} + \mathcal{N}_0}{h_{n,f,k}} \right)^{+}, \tag{19}$$

where ζ_f^m and ρ^m represent the Lagrangian multipliers related to the peak power budget constraint and interference constraint, respectively. Equation (18) includes also η_k the Lagrangian multiplier related to constraint (16) if the Min-Max utility is used. We can see from (17) that in Max C/I approach, all resources are allocated to the secondary users with favorable channel and interference conditions. By comparing (18) with (17), we can see that η_k values control the priority of the power resource allocation. However, enhancing the worst case channel conditions (i.e., corresponding to the minimum rate achieved) could come at the expense of users with good channel conditions which leads to more fairness between the secondary users. In (19), a tradeoff between C/I and Max-Min approaches can be clearly deduced. The FBS transmission power depends directly on the product of the other user rates. This approach tries to avoid having any user with very low data rate and maximize the product of the secondary rates simultaneously.

V. Simulation Results

We consider 7 hexagonal LTE cells each with radius equal to 1 km. The primary network consists of one MBS at the center of each hexagonal cell and 6 PBSs distributed at the edges of each cell as shown in Fig. 1. The secondary network consists of 70 FBSs which follow a uniform distribution and are distributed in the area of interest with 3 users inside each FBS, hence, $K_{\text{tot}} = 210$. An orthogonal LTE transmission is assumed where the bandwidth of each FP is equal to 10 MHz (i.e.,equivalent to 50 orthogonal RBs) as shown is Fig. 1. By employing OFDMA with the RB allocation algorithm presented in Algorithm 1, we assume that all users connected with a PBS within the cell are protected from the co-channel interference caused by other PBSs as they are deployed sparsely. The maximum transmission power for MBS, PBS, and FBS are equal to 46 dBm, 30 dBm, and 20 dBm, respectively. We set the tolerated primary outage threshold to be $\gamma_{\text{out}} = 0.05$ and penetration loss to be $L_{\text{ow}} = 20$ dB [12]. We also set $a_0 = 21.45$ W and $b_0 = 354.44$ W for MBSs and $a_j = 7.4$ W, $b_j = 71$ W for PBSs. The shadowing standard deviation and noise power density are given as $\sigma_\xi = 8$ dB, $\mathcal{N} = -174$ dBm/Hz, respectively.

Fig. 2 compares the performance of the proposed scheme with the traditional case when all primary BSs are kept active and with uniform power distribution where equal power transmission over the RBs is assumed. It is assumed that the primary data rate and the primary interference thresholds are equal to $R_{th} = 1$ Mbps and $I_{th} = 20$ dBm, respectively. For instance, comparing to the traditional case, when all primary BSs are active and optimal power allocation is applied, we can see that the proposed scheme offers a significant amount of energy saving by switching off the redundant primary BSs. Indeed, during the low traffic where the number of primary users is equal to $U_{\text{tot}} = 100$, the total power consumption

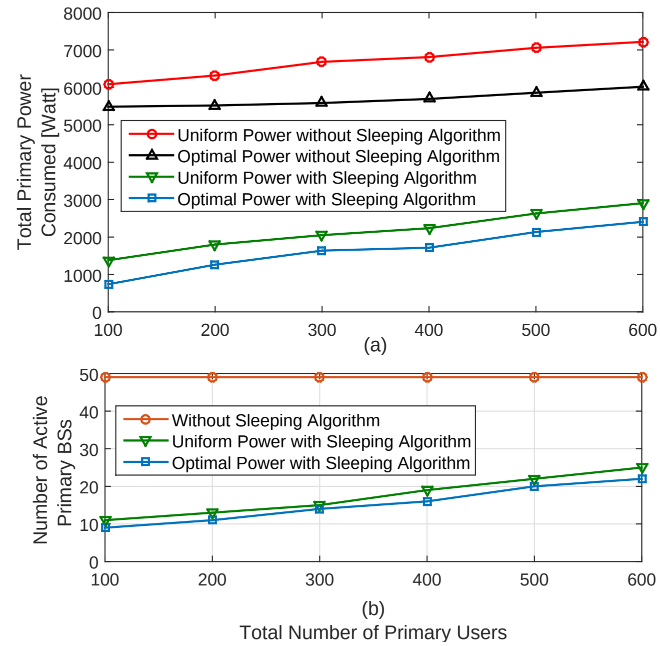

Fig. 2: (a) Total primary power consumption, (b) Number of active primary users, versus total number of primary users.

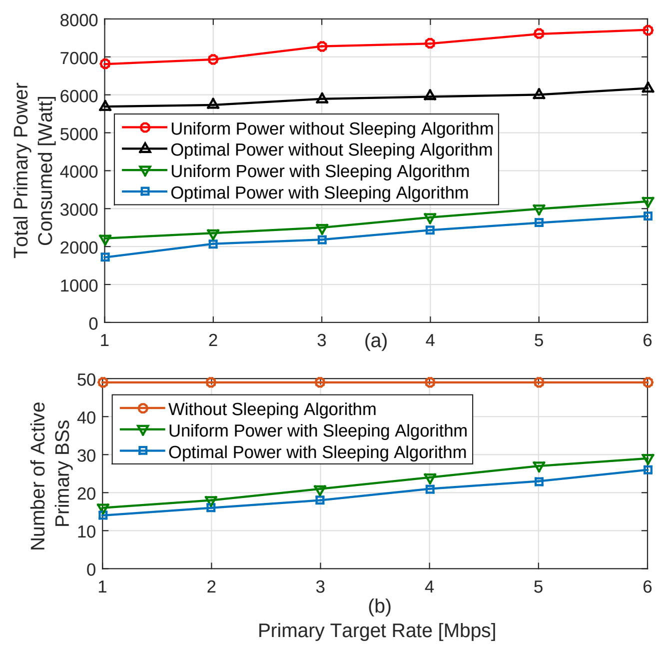

Fig. 3: (a) Total primary power consumption, (b) Number of active primary users, versus primary target data rate.

is reduced by around 5.5 times, while this gap decreases as the traffic becomes heavier (i.e., number of users increases). Also, the figure shows that the proposed scheme overcomes the uniform power distribution. Fig. 2-b shows that the number of active BSs increases as the number of users increases in order to satisfy the outage constraints $\frac{U_{\text{out}}}{U_{\text{tot}}} \leq \gamma_{\text{out}}$.

Similar observations can be made from Fig. 3 when the primary data rate threshold increases. In Fig. 3, we plot the performance of the proposed scheme for different R_{th} values with $I_{th} = 20$ dBm and $U_{\text{tot}} = 400$. The figure shows that as the target data rate increases the required power consumption to supply the network increases. It can be shown that the proposed scheme activates additional primary BS as R_{th} increases. For instance, for $R_{th} = 6$ Mbps, the total primary power consumption is reduced by around 50% by going from around 6000 Watt to around 3000 Watt using the proposed scheme instead of the traditional scheme where all BSs are active and employed optimal power allocation. Also, we can deduce that, thanks to the sleeping strategy, the proposed scheme can increase the target data rate dramatically from 1 Mbps to 6 Mbps by activating only few BSs (i.e., activate around 27 BSs instead of 14 BSs).

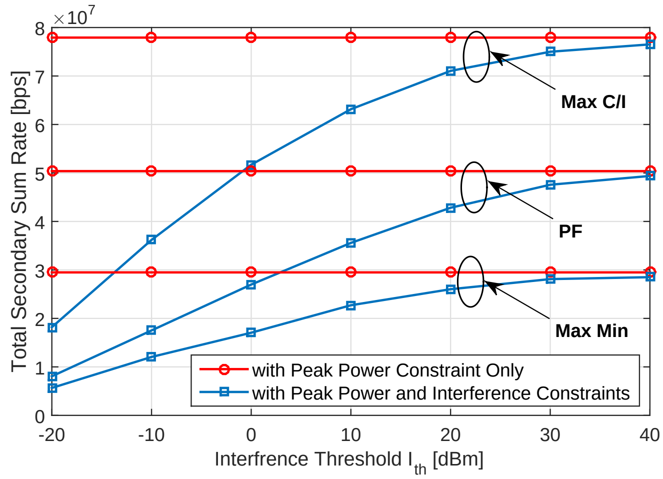

Fig. 4: Total secondary sum rate as a function of interference threshold I_{th}.

Finally, in Fig. 4, we aim to investigate the impact of the interference threshold constraint on the secondary system performance. In this figure, we plot the total secondary data rate versus I_{th} for different secondary utilities (Max C/I, Max-Min, PF) with the case of heavy primary traffic (i.e., $U_{\text{tot}} = 600$) and $R_{th} = 1$ Mbps. The proposed scheme is compared to the case when only the peak power constraint is applied. It can be shown that the proposed optimal solution when both constraints are considered (i.e.,power constraint and interference constraint) is upper bounded by the case when only power constraint is applied. It is shown that Max C/I utility leads to the highest secondary data rate in the network. However, this comes at the expense of fairness. The choice of the utility is related to the service used to the secondary users. For example, if it consists of a pure cognitive transmission without priorities, then Max C/I could be employed by allocating most of the resources to the user corresponding to the best channel and interference conditions. However, if the application requires the same downlink rates, then Max-Min utility can be used. On the other hand, the PF approach maximizes the geometric mean for all the secondary users by allocating almost the same power to all secondary users.

VI. Conclusion

In this paper, we proposed and solved a green communication optimization problem for LTE HetNets with underlay CR networks. Since most of energy is consumed by MBSs and PBSs, the objective was based on minimizing the total power consumed by primary BS (MBSs and PBSs) and maximizing the secondary data rate utility while satisfying a certain primary target rate and a certain primary interference tolerated threshold. More specifically, we optimized the primary and secondary resource allocation adaptively. Moreover, we investigated different utilities to introduce more fairness among secondary users. Our numerical results showed that the performance of the optimal proposed method achieved better performance compared to the traditional scenarios.

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