Energy Optimization of a Cellular Network with Minimum Bit-Rate Guarantee

(Invited Paper)

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***Abstract*—Energy optimization in cellular networks has been studied using different perspectives in the literature: sleep patterns, network interference, association of users and base stations, resource allocation of resources (bandwidth and power), etc. All these means have been discussed individually in previous works. However, none of the existing works has succeeded in proposing an exact mathematical model that takes into account several of these parameters simultaneously.**

In this article, we propose a first exact modelling of several network parameters and their interaction in order to minimize the energy consumption in a LTE cellular network. The optimization model guarantees to satisfy all the users with a minimum quality of service (data rate). Its exact solution allows energy savings of up to 50% in a moderately loaded network, which leads to energy savings up to twice that of the heuristic proposed by Piunti *et al.*, (2015). Various numerical results are presented on hexagonal and randomly generated cellular networks.

I. INTRODUCTION

Global mobile data traffic increased by 74% in 2015 and is expected to reach a compound annual growth rate of 53% by 2020. The number of mobile devices and connections worldwide is expected to reach 11.6 billion by 2020. This includes not only the 8.2 billion personal portable or mobile devices but also 3.2 billion M2M connections, e.g., GPS systems in cars, goods tracking systems in shipping and manufacturing sectors, medical applications making patient records and health status more readily available. North America is experiencing the fastest growth of mobile devices and connections with a 22% CAGR between 2015 and 2020, [1], [2]. This is an indication of the gigantic size of the mobile communications industry.

This growing number of mobile devices is causing a continuous increase in the energy consumption of cellular networks. The typical cellular network consists of three main elements: the core network (interface to fixed network), base stations and mobile terminals. At present, most of the energy in mobile networks (up to 80%) is consumed by base stations. There is an increased number of installed base stations (BSs) worldwide and, as a consequence, there is a significant growth of the total energy consumed by BSs of cellular network operators [3], [4], [5]. However, base stations are often underutilized as cells cover limited areas where users tend to exhibit similar behaviors, so that the load profile exhibits large variations between peak and off-peak values, with long periods of low load [6], [7]. Network operators plan their deployment with respect to peak traffic usage and are worried about the the quality of service (QoS) of their users and the offered data rates [8]. As the power consumption of BSs are not load proportional, it is however difficult to achieve energy efficiency under low loads.

Sleep mode is considered as one of the most powerful approaches to minimize the energy consumption in cellular networks [9]. The proposition is to put weakly loaded base stations into sleep mode or discontinuous transmission (DTX) mode during the off-peak hours. In a sleep mode, a base station serves no user and consumes a minimum amount of energy. In other words, BS capacity should be available only when and where it is needed; it is not necessary be always on [10].

However, switching off base stations results in aggregate interference reduction as well as in larger distances between users and serving base stations [11]. Base stations sleeping algorithms and strategies must consider the QoS of the users in the network. When a base station is switched off, the neighbouring base stations must provide coverage over any region which is no more covered by switched off base stations. On the other hand, increasing the energy of neighbouring base stations result in higher interference. In summary, interference, coverage, available channels and user assignment problems must be studied jointly to obtain an energy/performance trade off [12]. The ultimate goal is to redirect sufficient power over an adequate number of channels so that mobile operators can always guarantee the same QoS and data rates to users.

In this work, a linear optimization *accurate* model is proposed to minimize the power consumption of a LTE cellular network while affording a minimum data rate for each mobile terminal. The optimization framework finds the solution for the users, power and bandwidth assignment problems, using a SINR interference model. The optimization model is been solved exactly for LTE networks with up to 20 base stations and 450 users. For a given traffic, it outputs the best set of active base stations to serve the users, the user assignment and the resource allocation, while guaranteeing each user with the minimum required data rate.

The paper is organized as follows. Previous related studies are reviewed in Section II. Section III gives the detailed problem statement and the newly proposed network optimization model. Then, in Section VI, we present the solution process. In section V the heuristic of [10] is briefly described. Numerical results and a comparison with the heuristic of [10] are presented in Section VII. Conclusions are drawn in the last section.

II. LITERATURE REVIEW

Several studies have already looked into the issues pertaining to coverage, throughput, and energy trade-offs in cellular networks

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[13], [14]. The main goal is to take advantage of available network resources to reduce the energy consumption. A first set of studies relate to single single cells, and investigate the radio transmission processes in order to reduce the energy consumption. Several parameters have been investigated, and numerous studies exists, see, e.g., [15]. More recently, studies have investigated beamforming and MIMO techniques [16], [17].

A second set of studies deal with multi-cell wireless networks, see, e.g., [18] for a rather recent survey. Green scheduling and power control for both classic and heterogeneous cellular networks are reviewed in [19]. For some recent studies related to 5G and MIMO technology, see, e.g., [17].

In this paper, we are interested in exact methods for energy optimization in LTE networks. While there have been many studies with decomposition techniques for throughput and energy optimization for a single BS ([20], [21], [22]), there exists still no study with those techniques for LTE networks. This is explained by the fact that the problem resembles some location problems [23], for which column generation need to be combined with other techniques in order to be efficient.

We will focus on the sleep mode, one of the classical mechanism for energy efficiency. Previous studies for LTE networks include [24], where a user association scheme based on cell sleeping has been proposed to reduce the energy consumption under a simplifying strategy in which equal bandwidth scheduling. In [10], Piunti *et al.* proposed an iterative heuristic method for the cellular network configuration with QoS guarantee. The proposed solution determines the user association, bandwidth allocation, identification of active base stations and their transmission power. The iterative method is based on a Mixed Integer Quadratic Programming (MIQP) model that decides on BS-UE assignment together with the base stations activity. User bandwidth, and the transmit power of each active base station are then determined using different algorithms (see Section V for more details). However, this iterative solution does not necessarily provide the optimum solution. The accuracy of the result provided by this solution decreases as the size and traffic of the network growth and the network interference increases, see Section VII.

In this paper, we propose a model that minimizes the power consumption while taking the interference constraints accurately into consideration using a SINR modelling. The output of the model consists of the BS-UE assignment, the value of the transmission power of each base station, the selection of the base stations to be put in sleep mode and the bandwidth assigned to each user. This is the first work in the literature that finds the optimal user-base station assignment and resource allocation, while guaranteeing to satisfy each user with a minimum bit rate.

III. MINIMIZING ENERGY CONSUMPTION IN A CELLULAR NETWORK

A. Statement of the ECCN Problem

A cellular network is a wireless communication network which provides coverage over a geographic area by dividing the land into smaller cells. Mobile user equipment (UE) in each cell are covered by a fixed location transceiver known as a base station. The most common example of a cellular network is the mobile phone network where a wide geographic area (e.g., a city) is divided into smaller cells so that each mobile user can receive or make a call through a base station.

For a given distribution of the users over a geographical area, the ECCN problem aims at minimizing the total energy of the cellular network by deciding on UE-BS association and resource (power and bandwidth) allocation. In the solution output by the model, all users must be covered with a base station and satisfied with the minimum required data-rate. Moreover, allocated resources (power and bandwidth) at each base station cannot exceed the maximum available limit. In short, while assigning each user to a base station, the optimization model decides on the power transmitted and bandwidth allocated to the user.

B. Parameters

We denote by B the set of base stations and U the set of users assuming their locations to be distributed over a given area. Following is the set of variables and constants used in the optimization model.

1) Variables: The binary variable a_{bu} expresses the coverage association between base stations and users. $a_{bu} = 1$ if the user u is assigned to the base station b and $a_{bu} = 0$ otherwise. w_{bu} and p_{bu} are resource allocation variables: w_{bu} is the bandwidth allocated and p_{bu} is the power transmitted to u by base station b. I_b is the activity binary variable of each base station: $I_b = 1$ if the base station b is active and $I_b = 0$ if b is in sleep mode.

2) Constants: σ_{bu} is the channel gain between b and u. N_0 is the noise PSD. W is total bandwidth available at each base station. $P_{\max}$ is the base station transmission power limit. r_u is the minimum data rate required for each user. $p_{\min}$ is the user sensitivity: it is the minimum power that each user equipment needs to receive in order to operate. N_{bb} is the number of available bandwidth blocks at each base station.

C. Quality of Service and Achievable Data Rate

Quality of service (QoS) refers to the overall performance of the network, which depends on several characteristics, i.e. data rate, throughput, delay, etc. In this work, we focus on the data rate received by each user, as this is the only characteristic which is highly dependent on the transmission power. Using Shannon-Hartley theorem and taking interference into consideration, maximum achievable data rate (channel capacity) can be calculated as follows:

$$r_u = \sum_{b \in B} a_{bu}\, w_{bu}\, \log_2(1 + \text{SINR}_{bu}),$$

and SINR can be calculated using:

$$\text{SINR}_{bu} = \frac{p_{bu}\, \sigma_{bu}\, a_{bu}}{\dfrac{w_{bu}}{W}\left(\displaystyle\sum_{b' \in B} P_{b'} I_{b'} \sigma_{b'u}(1 - a_{b'u}) + W N_0\right)} \qquad (1)$$

where P_b is the total transmission power of b.

D. Base station Energy Consumption Model

In the deepest sleep mode, the energy consumption is very close to zero. It is assumed that a cell can go to a sleep mode very quickly, while going back to the active mode takes a certain amount of time and energy based on the sleep mode level. The idea behind a lighter sleep mode is is to deactivate only selected parts of the cell hardware so that the activation process becomes faster [25]. It this work, we consider a single sleep mode.

While in sleep mode the base station consumes a constant power (depending on the sleep level), its energy consumption depends on its load in the active mode. In general, energy consumption of a base station can be modelled as follows [26]:

$$P = \begin{cases} P_0 + \Delta_p . P_{\text{OUT}}, & 0 < P_{\text{OUT}} \leq P_{\max} \\ P_{\text{SLEEP}}, & P_{\text{OUT}} = 0, \end{cases} \tag{2}$$

where P_0 is the power consumption at the minimum non-zero output power, Δ_p is the slope of the load-dependent power consumption and P_{SLEEP} is the power consumption of the BS when in the sleep mode.

IV. ECCN Optimization Model

The objective function is written as follows:

$$\min \qquad \sum_{b \in B} (\Delta_p . P_b + P_0) I_b + P_{\text{SLEEP}} (1 - I_b). \tag{3}$$

The goal is to minimize the global power consumption of the network. I_b is the activity variable of base station b. It is equal to 1 if b is active and is 0 if it is in sleep mode.

Constraints can be expressed as follows:

$$\sum_{b \in B} a_{bu} = 1 \qquad u \in U \tag{4}$$

$$\sum_{b \in B} a_{bu} w_{bu} \log(1 + \text{SINR}_{bu}) \geq r_u \qquad u \in U \tag{5}$$

$$a_{bu} \leq \frac{p_{bu} \sigma_{bu}}{p_{\min,}} \qquad u \in U, b \in B \tag{6}$$

$$\sum_{u \in U} p_{bu} \leq P_{\max} \qquad b \in B \tag{7}$$

$$\sum_{u \in U} a_{bu} w_{bu} \leq N_{prb} \qquad b \in B \tag{8}$$

$$\varepsilon \sum_{u \in U} a_{bu} \leq I_b \leq M \sum_{u \in U} a_{ub} \qquad b \in B \tag{9}$$

$$p_{bu} \geq 0, a_{bu} \in \{0, 1\}, w_{bu} \in \{1..N_{bb}\} \quad u \in U, b \in B \tag{10}$$

$$I_b \in \{0, 1\} \qquad b \in B. \tag{11}$$

All users must be covered and satisfied. Constraint (4) forces each user to be assigned to exactly one base station. Constraint (5) is the bit-rate constraint: it guarantees that each user is satisfied with the minimum required data rate. Note that the minimum required data rate, r_u, depends on each user, so that different users can be provided with different data rates. Constraint (6) provides each user with a minimum power, which should be greater than or equal to the user sensitivity. Constraint (7) is the upper bound constraint for the transmission power of each base station. Constraint (8) enforces a limitation on the maximum number of bandwidth blocks each base station can provide. Constraint (9) determines activity of base stations. Each base station is active if it is serving at least one user. If no user is assigned to a base station, then it will be put in sleep mode. Note that ε is a small and M is a large number.

V. Heuristic Solution of [10]

In this section, we briefly recall the model and the `MinPowerQoS` algorithm proposed by [10]. In this work, the authors propose a heuristic to solve the ECCN problem. A multi-phase algorithm is used to deal with the non-linear bitrate constraint and to find a solution to ECCN optimization model, see [10] for more details. We will compare our results with those of [10] in Section VII. In the solution of [10], an MIQP is defined initially which is a simplified version of the ECCN: the bandwidth assignment and bit rate constraints from ECCN optimization model are removed, i.e., constraints (5) and (10) of ECCN model are omitted and constraints (8) are replaced by the following ones:

$$\sum_{u \in U} a_{bu} \leq N_{prb} \qquad b \in B. \tag{12}$$

This MIQP decides on BS-UE assignment only. Since the MIQP does not include the non-linear constrains, it can be solved using an Integer Linear Program (ILP) solver. The provided solution determines the BS-UE association. However, the bandwidth allocation and power assignment is not taken care by the MIQP model and it will be done in a second step. Several algorithms are suggested in [10] for the bandwidth assignment i.e., we can consider the equal bandwidth assignment algorithm and divide the available bandwidth blocks at each base station equally among the assigned users. Given a BS-UE association and a bandwidth assignment, the power control algorithm suggested in [10] provides the optimum BS transmission power. After applying power control to determine the transmitting power, the received users data rate is calculated. For any user who is not satisfied with the minimum data rate, its minimum required power is increased and the MIQP is solved again. The algorithm iterates until all users are satisfied or there is no feasible solution to the MIQP.

```
Data: $\sigma_{ub}, p_{min}, P_{\max}$
Result: $a_{ub}, w_{ub}, p_{ub}, I_b$
$p_{\min,u} = p_{\min}; u \in U$;
while not all the users are satisfied do
    Solve MIQP;
    Do the bandwidth and power allocation;
    forall users do
        Calculate user data rate;
        if the user is not satisfied then
            increase $p_{\min,u}$;
        end
    end
end
```

Algorithm 1: MinPowerQoS

Note that `MinPowerQoS` does not necessarily provide an optimal solution. User-base station assignment and resource allocation is done in two steps and the assignment step does not take the bandwidth limitations, interference and bit-rate constraint into consideration. As can be seen in the numerical results in Section VII, this does not impact too much the power consumption of the network when the network load is low. However, when the load increases, with a high number of interferences, the gap between the exact solution (see Section VI) and the solution of this heuristic iterative process increases.

VI. Exact Solution of the ECCN Problem

The bit-rate constraint (5) of the ECCN optimization model described in section IV is logarithmic and therefore is not linear. In order to deal with non-linearity and solve the ECCN model, an exact linearization is proposed in this section.

In order to perform the linearization, we define a set of constants $T^{r,w}$: for each data rate r and bandwidth w, $T^{r,w}$ is the minimum SINR required for a user who is assigned a bandwidth

w, and who requires a rate r. Value of $T^{r,w}$ is given by the following formula:

$$T^{r,w} = 2^{\frac{r}{w}} - 1.$$

For each user, if the received SINR is greater than $T^{r,w}$, then we can conclude that the bit-rate received by the user is greater than r.

A new $0-1$ variable c_{ub}^{w} is defined in order to select the right threshold for each user:

$c_{bu}^{w} = 1$ if user u is assigned the bandwidth w by base station b, 0 otherwise.

Using variable c_{ub}^{w} and constant $T^{r,w}$, constraints (5) can be equivalently rewritten:

$$\sum_{b\in B} a_{bu}\text{SINR}_{bu} \geq \sum_{b\in B}\sum_{w\in W} c_{bu}^{w} T^{r,w} \qquad u \in U. \tag{13}$$

For each user, the left-hand side of (13) is the SINR that the user receives and the right-hand side is the minimum required SINR threshold.

Combining (1) with (13), and after performing some algebraic manipulations, constraint (13) can be equivalently rewritten:

$$\sum_{b\in B}\sum_{w\in W} \frac{c_{bu}^{w}\sigma_{bu}p_{bu}W}{T^{r,w}} - P_b\sigma_{bu}(1-a_{bu}) \geq WN_0 \qquad u \in U. \tag{14}$$

where $P_b = \sum_{u\in U} p_{bu}$ is the total power that base station b consumes.

The new variable c_{ub}^{w} needs to also satisfy the next two set of constraints:

$$\sum_{w\in W} c_{bu}^{w} \leq 1 \qquad u \in U, b \in B \tag{15}$$

$$\sum_{u\in U}\sum_{w\in W} c_{bu}^{w} \times w \leq W \qquad b \in B \tag{16}$$

where constraints (15) force each user to be assigned at most one specific number of bandwidth blocks only, and constraints (16) guarantee that the total number of assigned bandwidth blocks at each base station does not exceed the number of available bandwidth blocks.

In other words, the logarithmic constraint (5) of the optimization model (4)-(11) is replaced by the above linear constraints (14), (15) and (16). Note that the proposed linearization is exact and does not alter the model constraints and limitations. The solution of the resulting model is therefore exact and will be referred to `OptPowQoS` in the sequel.

VII. NUMERICAL RESULTS

We implemented the solutions described in sections V and VI, using IBM ILOG CPLEX Optimization Studio 12.6.0.0. With the analysis of the solutions on various data sets, we evaluate the power consumption savings due to the base station sleep mode and the transmission power adaptation.

The solutions are compared with the upper bound and a lower bound. As an upper bound, the `ClosestBSMapping` algorithm suggested in [10] is used. It assigns each user to its closest base station and then uses the power control algorithm suggested in [10] for power allocation. In this upper bound solution, available bandwidth blocks are divided equally among the users. As a lower bound, the `MinPower` algorithm suggested in [10] is used. It solves the assignment and power allocation problems without considering the constraint of minimum data rate required for each user. Let's call the exact solution described in section VI by `OptPowQoS`. The difference between the solution provided by `MinPower` and the solutions provided by `OptPowQoS` shows the cost of satisfying users with the minimum bit rate constraint (in terms of energy consumption).

We first describe the data sets (section VII-A). We next evaluate the achievable power consumption savings by solving the exact proposed solution of `OptPowQoS` (section VII-B). Results are then compared with those of the heuristic proposed by Piunti *et al.* [10] (section VII-C).

A. Data Sets and Setting of the Parameters

For each base station, the maximum transmission power is limited to 20 watts. Each base station has a total bandwidth of 5 MHz divided into 25 bandwidth blocks (each 0.180 MHz). The users are distributed uniformly in a circle of radius $R = 1100$ meters. User sensitivity is -174 dBm/Hz. Channel gain between the users and base stations is modelled using $\sigma = \frac{1}{10^{-0.1L}}$ where $L = 15.3 + 37.6\log d$ and d is the distance between the user and the base station. Noise PSD is -174 dBm/Hz. All reported results correspond to average over 5 traffic instances.

B. Power Consumption Savings

In this section we evaluate achievable power saving by solving the ECCN problem using `OptPowQoS`. Results are compared with the `ClosestBSMapping` upper and the `MinPower` lower bounds. The network consists of 19 base stations distributed on a hexagonal grid with the inter-site distance of 500 meters. Users data rate demands are modelled using an exponential distribution with an average of 64 kbps and a maximum of 8 Mbps (Any demand greater than 8 Mbps is satisfied with 8Mbps). The average needed data rate by the users in a mobile network is less than 64kbps even during the peak hours [27]. The maximum of 8 Mbps is based on streaming a High Definition (HD) video which needs a bandwidth of 5-8 Mbps.

Figure 1 and 2, respectively, show power consumption and number of active base stations based on the number of users in the network. Simulation results show that in a network with a moderate load, more than 50% of energy saving can be archived by doing the proper assignment and resource allocation. While by assigning each user to its closest base station, energy consumption of the network grows extremely fast, it grows almost linearly with the number of users when using the solution provided by `OptPowQoS`. Moreover, the model becomes infeasible almost 2 times faster by assigning each user to the closest base station. As the number of available bandwidth blocks and amount of energy at each base station is limited, having many users around any base station makes it infeasible to cover all users using the closest BS assignment. However, this case can be managed properly by solving the problem using `OptPowQoS`. Total number of bandwidth blocks in the simulated network is 475 and `OptPowQoS` allows satisfying up until 440 users.

C. Comparison results with the heuristic of [10]

In this section we compare the results obtained by `OptPowQoS` with the results obtained by the heuristic of [10] described is section V (`MinPowerQoS`). Figures 3 to 6 provide the simulation results of the two different solution schemes, and of the lower and upper bounds, on different networks. The targeted data-rate for this simulation is 256 kb/s for all users. We consider two

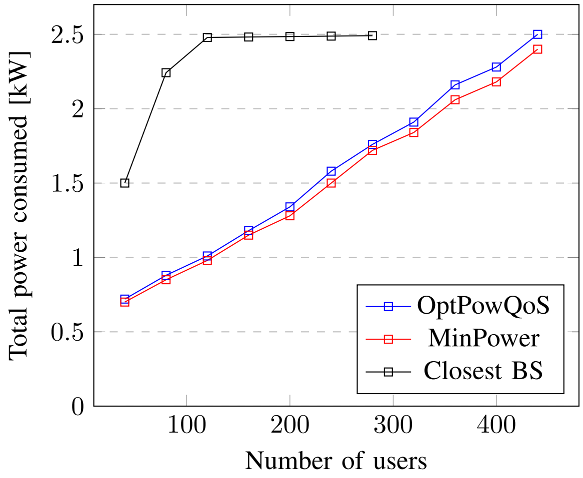

Fig. 1. Total power consumption in LTE hexagonal grid networks

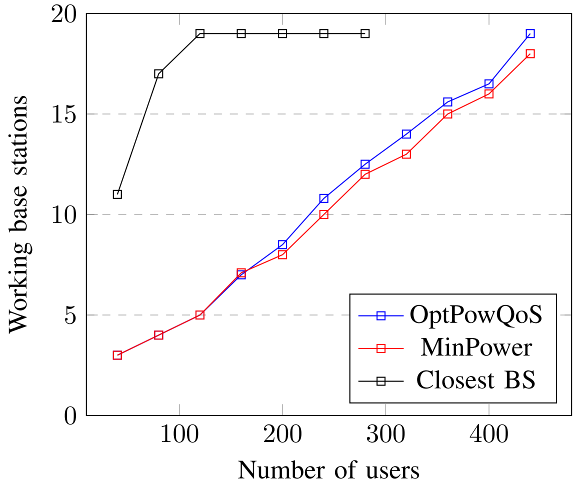

Fig. 2. Active base stations in LTE hexagonal grid networks

different cell configuration networks. The first one consists of 19 base stations distributed on a hexagonal grid with an inter-site distance of 500 meters. The second network consist of 20 base stations uniformly distributed in a circle with a radius of 1,000 meters with no two base stations closer than 300 meters.

Figure 3 and 4 show the power consumption and the number of active base stations of the LTE hexagonal network based on the number of users. Figures 5 and 6 show the total power consumed and number of active base stations based on the number of users for the randomly generated networks.

We observe that for low traffic load scenarios, the solution provided by `MinPowerQoS` is very close to the optimum solution of `OptPowQoS`. However, for a busy and high loaded network, the solution provided by the iterative heuristic algorithm becomes less accurate. This is because of the increased interference in the network. For a network with 200 users, the heuristic solution is up to %35 off the optimal solution. Moreover, the `MinPowerQoS` algorithm fails to find the solution when the network traffic increases to around 300 users. In the optimal solution, energy consumption increases linearly with the network traffic. Note that the `MinPower` solution does not take interference into consideration, while the exact solution guarantees a received bit rate for each user, taking interference into account.

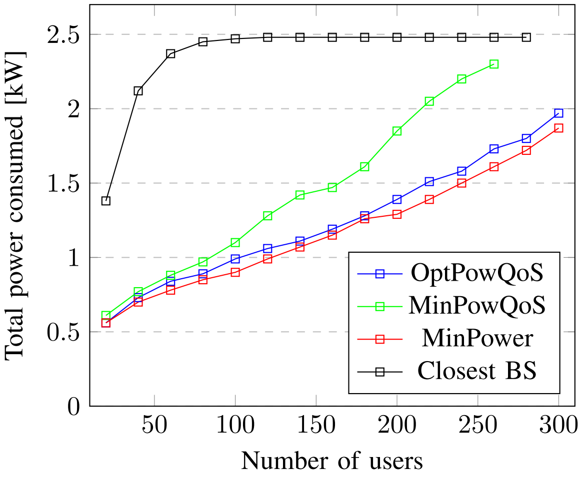

Fig. 3. Total power consumption in LTE hexagonal grid networks

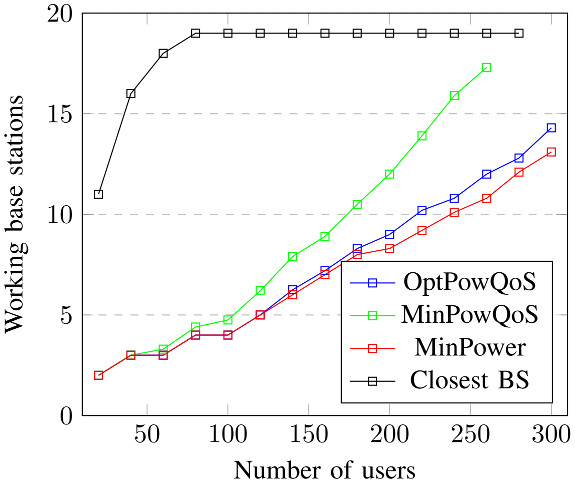

Fig. 4. Number of active base stations in LTE hexagonal grid networks

Comparing *MinPower* and the exact solution, we notice that the cost of satisfying users with the minimum bit rate is not high in terms of the energy consumption. In the simulated networks, the exact solution is always less than only %10 higher than the solution provided by the *MinPower* algorithm.

VIII. CONCLUSIONS

We designed a novel exact optimization model that minimizes the power consumption with guaranteed QoS in a cellular network. While previous heuristic solutions showed that in moderate load scenarios, by putting the cells in sleep mode, up to 25% power savings can be achieved with respect to the basic scheme, exact solution shows that additional power saving can be obtained, e.g., up to 50% in a moderate load scenario when the network is half-loaded. In addition, more users can be covered and satisfied using the optimal solution in comparison with the usual closest base station mapping strategy. The optimal solution provided by the exact optimization model finds the maximum achievable energy saving in a cellular network and evaluates the results quality of any other proposed heuristic. Future work will include increasing the scalability of the exact model and solution in order to be able to solve larger data instances. Most likely, it means using a decomposition model and the sue of large-scale

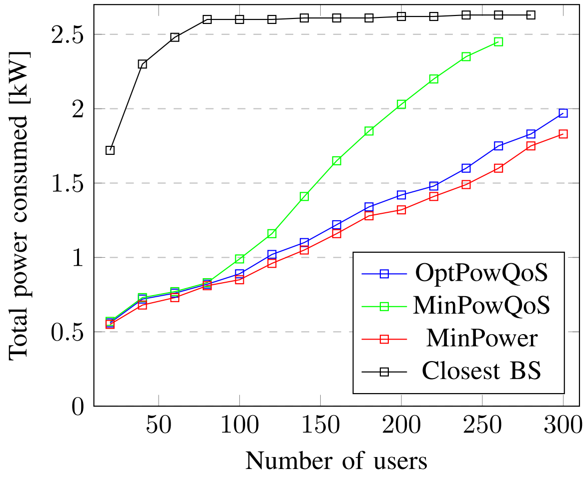

Fig. 5. Total power consumption in randomly generated networks

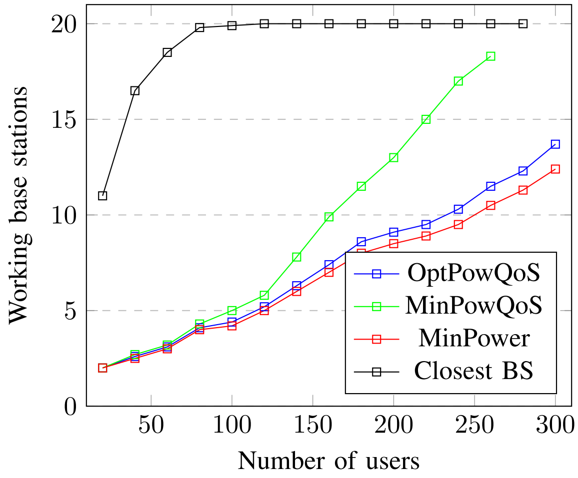

Fig. 6. Number of active base stations in randomly generated networks

optimization algorithms, while for real time algorithms, we need to recourse to heuristics.

ACKNOWLEDGMENT

B. Jaumard has been supported by a Concordia University Research Chair (Tier I) and by an NSERC (Natural Sciences and Engineering Research Council of Canada) grant.

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