Joint Power-Delay Minimization in 4G Wireless Networks

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Abstract—**In this paper, we formulate an optimization problem that jointly minimizes the network power consumption and the transmission delay in broadband wireless networks. Power saving is achieved by adjusting the operation mode of the network Base Stations (BSs) from high transmit power levels to low transmit levels or switched-off. Whereas, minimizing the transmission delay is achieved by selecting the best user association with the BSs. We study the case of a realistic Long Term Evolution (LTE) Network where the challenge is the high computational complexity necessary to obtain the optimal solution. Thus, in this paper, we propose a simulated annealing based heuristic algorithm for the power-delay minimization problem. The proposed heuristic aims at computing the transmit power level of the network BSs and associating users with these BSs in a way that jointly minimizes the total network power and the total network delay. Simulation results show that the proposed algorithm has a low computational complexity which makes it more advantageous compared to the optimal scheme. Moreover, the heuristic algorithm performs close to the optimal and outperforms the existing approaches in realistic 4G deployments.**

I. INTRODUCTION

In the past years, operators have focused on technological developments to meet capacity and Quality of Service (QoS) demands of the User Equipments (UEs). Recently, pushed by the needs to reduce energy, mobile operators are rethinking their network design for optimizing its energy efficiency and satisfying user QoS requirements.

Knowing that over 80% of the power in mobile telecommunications is consumed in the radio access network, more specifically at the base stations (BSs) level [16], a lot of research activities focused on improving the energy efficiency of broadband wireless networks. In [16] [18], different network deployment strategies were studied and simulations showed that the use of low power BSs improves the network energy efficiency. In [10], authors studied the coverage planning in cellular networks taking into account the sleep mode and the power adjustment for energy saving. Authors in [9] proposed an energy efficient algorithm in cellular networks based on the principle of cooperation between BSs. In this algorithm, the BSs dynamically switch between active/sleep modes or change their transmit power depending on the traffic situation.

In the literature, there are quite few examples which consider the QoS (such as delay, blocking probability, etc) as an important criteria. Among them, authors in [8] used deterministic patterns for switching BSs through mutual cooperation among BSs. QoS is guaranteed by focusing on the worst case transmission/reception location of the UE situated in the switched-off cell. Authors in [5] dealt with the Long Term Evolution-Advanced (LTE-A) Standard. They proposed a greedy heuristic algorithm to switch off a BS according to the average distance of its users, and without compromising the outage probability of the UEs. The authors in [14] proposed a centralized and a decentralized cell zooming algorithms based on the transmission rate requirements of the users and the capacity of the BSs. The proposed algorithms leverage the tradeoff between energy consumption and outage probability. The authors in [17] formulated a joint minimization problem that allows for a flexible tradeoff between flow-level performance and energy consumption. Users are associated to BSs in such a way to minimize the average flow delay, and greedy algorithms are proposed for switching on/off the network BSs. [17] studied only the case where BSs switch between on and off modes without adjusting their transmit power.

In this paper, we tackle the joint optimization problem of power saving and transmission delay minimization in LTE networks. Specifically, power saving is achieved by adjusting the operation mode of the network BSs from high transmit power levels to low transmit levels or switched off. In this context, changing the operation mode of the BSs is coupled with user association. Such coupling makes solving the problem more challenging. Furthermore, minimizing the transmission delay is achieved by selecting the best user association with the network BSs.

Our approach presents multiple novelties compared to the state-of-the-art: *i)* we formulate the power-delay minimization problem as an non-linear optimization problem. This formulation enables us to evaluate the tradeoffs between minimizing the network power consumption and the network delay. *ii)* Our formulation captures the specificity of LTE technology in terms of power model and radio resource allocation. *iii)* Unlike, most of the previous studies, we combine the different green approaches (BS on/off mode, adjustment of BS transmit power, user association) to provide power saving. Due to the high computational complexity of the Power-Delay-Min problem, we propose in this paper with a novel Simulated Annealing (SA) based heuristic algorithm for this problem. The heuristic computes satisfactory solutions for the problem while keeping the computation complexity suitably low for practical implementations. Thus, we apply our heuristic to real life scale scenario.

Our heuristic is based on the SA technique which is a probabilistic searching method. The proposed heuristic aims at computing the transmit power level of the BSs deployed in the network and associating users with these BSs in a way that jointly minimizes the total network power and the total network delay. In order to evaluate the efficiency of the heuristic algorithm for the Power-Delay problem, we compare the results obtained by this heuristic with the optimal solution and the existing solutions.

The rest of the paper is organized as follows. In Section II, we describe the network model considering an LTE network. In Section III, we present the Power-Delay minimization problem. In Section IV, we present our proposed heuristic algorithm. In Section V, we present the existing approaches. In Section VI, we provide the simulation results. Conclusions are given in Section VII.

II. NEWORK MODEL

We consider an LTE network with N_{bs} BSs. We assume that the each BS operates in two modes: active and switched-off. We denote by N_l the number of transmit power levels of a BS. Transmitting at different power levels leads to different coverage area sizes. The indexes $i \in I = \{1, \ldots, N_{bs}\}$, and $j \in J = \{1, \ldots, N_l\}$, are used throughout the paper to designate, respectively, a given BS and its transmit power level. Note that, for $j = 1$ we consider that the BS transmits at the highest power level and for $j = N_l$ the BS is switched off. We term by $k \in K = \{1, \ldots, N_u\}$, the index of a given UE where N_u is the number of UEs in the network.

A. Traffic and Delay Model

In this paper, we only consider the downlink traffic since it is several orders higher than the uplink one. We assume that *i)* the network is in a static state where UEs are stationary, *ii)* the network is in a saturation state. A saturation state is a worst case scenario where every BS has persistent traffic toward UEs. Moreover, in the emerging cellular systems such as LTE networks, the Orthogonal Frequency Division Multiple Access (OFDMA) is adopted as downlink access method. The latter allows multiple UEs to transmit simultaneously on different subcarriers. As subcarriers are orthogonal, intra-cell interference is highly reduced. Furthermore, in order to mitigate the inter-cell interference, we use the Frequency Reuse 3 scheme. This scheme consists of dividing the frequency band into 3 subbands and allocates only one subband to a given cell, in such a way the adjacent cells use different frequency bands [6].

1) Radio Conditions: The peak rate of a given UE is defined as the throughput experienced by the UE when alone in the cell. The peak rate of each UE depends on its received Signal to Noise Ratio (SNR). We denote by $\chi_{i,j,k}$ the peak rate perceived by UE k from BS i transmitting at power level j.

2) Data Rate Model: In OFDMA, the system spectrum is divided into a number of channels; each channel consists of a number of consecutive orthogonal OFDM subcarriers. The Resource Block (RB) is the smallest resource unit that can be scheduled. An RB is a single channel for the duration of one time slot, and a consecutive number of slots constitute a frame. In this paper, we consider a flat channel model where each UE has similar radio conditions on all the RBs. Moreover, we consider a fair-time sharing model where RBs are cyclically assigned with equal time to UEs within a given cell. These UEs are given the same chance to access the RBs. Based on the mentioned considerations and as UEs are stationary, the scheduler is thus equivalent to a scheduler that allocates all RBs to one UE at each scheduling epoch. Hence, when UE k is associated with BS i transmitting at level j, its mean throughput ($R_{i,j,k}$) depends on its peak rate ($\chi_{i,j,k}$) and on the number of UEs associated with this same BS, and it is given by [11]:

$$R_{i,j,k} = \frac{\chi_{i,j,k}}{1 + \sum_{k'=1,k' \neq k}^{N_u} \theta_{i,k'}}, \tag{1}$$

where $\theta_{i,k'}$ is the binary variable indicating whether UE k' is associated with BS i or not.

3) Delay Model: We denote by $T_{i,j,k}$ the amount of time necessary to send a data unit to UE k from BS i transmitting at level j. In fact, the bit transmission delay for a given UE is the inverse of the throughput perceived by this UE. Thus,

$$T_{i,j,k} = \frac{1 + \sum_{k'=1,k' \neq k}^{N_u} \theta_{i,k'}}{\chi_{i,j,k}}. \tag{2}$$

B. Power Consumption Model

Following the model proposed in the Energy Aware Radio and neTwork tecHnologies (EARTH) project [4], the power consumption of a BS is modeled as a linear function of the average transmit power as below:

$$\forall i \in I, p_{i,j} = \begin{cases} N_{TRX} \cdot (v\pi_j + w_j), & 0 < \pi_j \leq \pi_1, \\ \quad j = 1, \ldots, (N_l - 1); & \\ N_{TRX} \cdot w_{N_l}, \ \pi_{N_l} = 0. & \end{cases} \tag{3}$$

where $p_{i,j}$ and π_j denote respectively the average consumed power per BS i and the transmit power at level j respectively. In our paper, the BS is switched off for $j = N_l$. The coefficient v is the slope of the load-dependent power consumption and it accounts for the power consumption that scales with the transmit power due to radio frequency amplifier and feeder losses. The coefficients w_j, $j = 1, .., (N_l - 1)$, represents the power consumption at the zero output power (it is actually estimated using the power consumption calculated at a reasonably low output power, assumed to be 1% of π_1). These coefficients model the power consumption independently of the transmit power due to signal processing, power supply consumption and cooling. w_{N_l} is the coefficient that represents the sleep mode power consumption. N_{TRX} is the number of BS transceivers.

C. Coverage Area

Transmitting at different power levels leads to different coverage area sizes. Note that, all UEs within the coverage area of a BS require some minimum received SNR for acceptable performance. In our paper, a UE is thus considered covered by a BS if its SNR is above a given threshold. As mentioned in II-A1, the peak rate perceived by a given UE depends on its SNR. Consequently, a UE is covered if it perceives a peak rate, from at least one BS, higher than a given peak rate threshold ($\chi_{threshold}$).

III. Optimization Problem

A. Problem Formulation

Our approach is formulated as an optimization problem that consists in minimizing the power consumption of the network and the sum of the data unit transmission delays of all UEs. A key trade-off in our problem is between these two objectives. On the one hand, reducing the transmit power level of the BSs or switching them off to save energy may result in increasing the transmission delay (indeed, if there is no coverage constraints, then all BS could be switched off and no user is served: the transmission delay becomes infinite). On the other hand, to minimize the transmission delay, each BS should transmit at the highest power level possible.

The design variable in our Power-Delay problem is to decide what follows:

- The operation mode of the network BSs (on/off) and for active BSs, the corresponding transmit power level.
- The users association with the network BSs.

Let $\lambda_{i,j}$ be a binary variable that indicates whether BS i transmits at level j or not. $\lambda_{i,j}$ are the elements of the matrix Λ defining the operation mode of the network BSs. Let $\theta_{i,k}$ be a binary variable that indicates whether a user k is associated with BS i or not. $\theta_{i,k}$ are the elements of the matrix Θ defining the users association with the network BSs.

The Power-Delay-Min problem consists in computing the transmit power level of the BSs and in associating UEs with these BSs in a way that jointly minimizes the total network power and the total network delay. The *total network power*, denoted by $C_p(\Lambda)$, is defined as the total power consumption of active BSs in the network and is given by:

$$C_p(\Lambda) = \sum_{i \in I, j \in J} (a\pi_j + b) \cdot \lambda_{i,j}. \tag{4}$$

The *total network delay*, denoted by $C_d(\Lambda, \Theta)$, is defined as the sum of data unit transmission delays of all UEs in the network and is given by:

$$C_d(\Lambda, \Theta) = \sum_{i \in I, j \in J, k \in K} T_{i,j,k} \cdot \lambda_{i,j} \cdot \theta_{i,k} \tag{5}$$

Therefore, the *total network cost*, denoted by $C_t(\Lambda, \Theta)$, is thereby defined as the sum of power and delay components and is given by:

$$C_t(\Lambda, \Theta) = \alpha C_p(\Lambda) + \beta\beta' C_d(\Lambda, \Theta), \tag{6}$$

α and β are the weighting coefficients representing the relative importance of the two objectives. It is usually assumed that $\alpha + \beta = 1$ and that α and $\beta \in [0,1]$. β' is a normalization factor that will scale the two objectives properly.

Consequently, our Power-Delay-Min problem ($\mathcal{P}$) is given by:

$$\underset{\Lambda, \Theta}{\text{minimize}} \quad C_t(\Lambda, \Theta) = \alpha C_p(\Lambda) + \beta\beta' C_d(\Lambda, \Theta), \tag{7}$$

$$\text{subject to} \quad \sum_{j \in J} \lambda_{i,j} = 1, \quad \forall\, i \in I, \tag{8}$$

$$\sum_{i \in I} \theta_{i,k} = 1, \quad \forall\, k \in K, \tag{9}$$

$$\lambda_{i,j} \cdot \theta_{i,k} = 0, \quad \forall\, (i,j,k) : i \in I, j = N_l, k \in K. \tag{10}$$

Constraints (8) state that every BS transmits only at one power level. Constraints (9) ensure that a given UE is connected to only one BS. Finally, constraints (10) ensure that a given UE is not associated with a switched off BS.

B. Optimal Solution

($\mathcal{P}$) is a binary non-linear optimization problem. Such problem can be solved using an exhaustive search algorithm [12]. However, the complexity of searching only for the operation mode of the BS is in $\mathcal{O}(N_l^{N_{bs}})$. This makes the exhaustive search very computational intensive, and rapidly becomes intractable for modest sized networks. In [13], we converted ($\mathcal{P}$) into a MILP problem and used a branch-and-bound (BB) approach to solve it. In the latter approach, the number of integer variables determines the size of the search tree and impacts the computation time of the algorithm. Thus, we noted that our MILP conversion can not deliver solutions for realistic networks. Hence, in this paper we introduce a heuristic that computes satisfactory solutions for the problem while keeping the computation complexity suitably low for practical implementations.

IV. Heuristic Algorithm

Due to the high computational complexity of the Power-Delay-Min problem, we propose in this paper a novel SA heuristic algorithm for this problem. The proposed heuristic aims at computing the transmit power level of the BSs deployed in the network and associating users with these BSs in a way that jointly minimizes the total network power and the total network delay.

The SA algorithm includes an acceptance probability, which can prevent the algorithm from terminating at local minima. Such characteristic is very suitable to our problem. Moreover, there is a number of other features associated with the SA algorithm that is of particular appeal to our formulation: its ability to scale for large scale optimization problems, and its effectiveness against the exhaustive search [15].

Our heuristic starts with an initial feasible solution where all the network BSs transmit at the corresponding power level and all UEs are associated with the network BSs. Such solution determines the total network cost. Then, at each iteration, a BS is randomly chosen to change its transmit power level which is selected uniformly from the available power levels. For each change of the BS transmit power level, UEs are associated with the best BS according to Power-Coverage Based User Association (PoCo-UA) (explained later in Section IV-A1).

This is a candidate solution to be used and its total network cost is computed. The candidate solution is accepted as a current solution based on a certain probability. Typically, the steps are repeated until a given stop criterion is satisfied.

A. SA Heuristic Algorithm for the Power-Delay-Min Problem

Algorithm 1 describes the different steps of our SA heuristic algorithm for the Power-Delay-Min problem. The algorithm takes as inputs the number of BSs, the number of transmit power levels, the number of UEs in the network, and the initial solution: initial operation mode of the BS Λ^0, initial user association Θ^0, initial cost total network cost C_t^0 (Step 1). The algorithm outputs the operation mode of the BSs Λ_{SA}, the user association Θ_{SA} and the total network cost $C_{t_{SA}}$ (Step 2). Let $N_{iterations}$ denotes the maximum number of the algorithm's iterations and C_t^q denotes the total network cost at iteration q. Let ϵ be the precision parameter, and T be a positive constant. The algorithm starts with an initial feasible solution where all the network BSs transmit at the corresponding power level and all UEs are associated with the network BSs. Such solution determines the initial total network cost which is computed according to (6). Then, at each iteration, a BS is randomly chosen to change its transmit power level which is selected uniformly from the available power levels (Step 4). Afterwards, the coverage constraint is verified for all UEs in the network (Step 5). If all network UEs are covered then each UE is associated with the active BSs according to PoCo-UA (Step 6), and the total network cost C_t^* is computed according to (6) (Step 7). This is a candidate solution to be used. If the difference of the total network cost between the candidate solution and the current solution is negative, the candidate solution is directly taken as the current solution (Step 11). Otherwise, it is accepted as the current solution with probability $e^{(C_t^* - C_t^{q-1})/T}$ (Step 13). Typically, the iterations are repeated until a given stop criterion is satisfied. For instance, a maximum number of iterations has been exceeded (Step 3) or no more improvement in terms of total network cost can be achieved (Step 8). Once the stopping criteria is met, the algorithm outputs the operation mode of the BSs Λ_{SA} and the user association Θ_{SA} of the iteration q^{SA} that has the minimal total network cost $C_{t_{SA}}^{q_{SA}}$ (Steps 19 and 20).

1) Power-Coverage Based User Association (PoCo-UA): Algorithm 2 describes the different steps of PoCo-UA. The PoCo-UA algorithm takes as inputs the set of BSs covering UE k denoted by Ψ_k, and the number of UEs covered by BS ψ denoted by $c(\psi)$ (Step 1). It outputs the user association denoted by $\Theta_{PoCo-UA}$ (Step 2). For UEs covered by several BSs (Step 5), the algorithm proceeds as follows: each UE k computes two coefficients r_k^ψ and ρ_ψ^k for each of its covering BS $\psi \in \Psi_k$ (Step 7). These coefficients take into consideration respectively the received SNR at the UE side and the number of UEs covered by the corresponding BS. We combine these coefficients with a probability function in such a way that the probability to be associated with a given BS is proportional to the peak rate perceived by the UE and inversely proportional to the number of UEs covered by the corresponding BS. Then, each UE k computes $\delta_{\psi,k}$ the probability to be associated with BS ψ (Step 8).

Algorithm 1 SA Heuristic Algorithm for the Power-Delay-Min Problem

```
1: Input: $N_{bs}, N_l, N_u$, $\Lambda^0$, $\Theta^0$, $C_t^0$.
2: Output: $\Lambda_{SA}, \Theta_{SA}$, $C_{t_{SA}}$;
3: for $q$=1 to $N_{iterations}$ do
4:     compute new operation mode of the BS $\Lambda^*$;
5:     if $\forall k \in K, \exists (i,j) \in (I,J) / \chi_{i,j,k} \cdot \lambda_{i,j}^* \geq \chi_{threshold}$ then
6:         Compute the new user association $\Theta^*$ according to PoCo-UA;
7:         Compute $C_t^*$;
8:         if $\frac{|C_t^* - C_t^{q-1}|}{C_t^{q-1}} < \epsilon$ then
9:             break;
10:        else if $C_t^*$ - $C_t^{q-1} \leq 0$ then
11:            $C_t^q$ = $C_t^*$, $\Lambda^q$=$\Lambda^*$, $\Theta^q$=$\Theta^*$;
12:        else if $C_t^*$ - $C_t^{q-1} > 0$ then
13:            $C_t^q$ = $C_t^*$, $\Lambda^q$=$\Lambda^*$, $\Theta^q$=$\Theta^*$ with probability $e^{(C_t^* - C_t^{q-1})/T}$;
14:        end if
15:    else
16:        Go to Step 4;
17:    end if
18: end for
19: $C_{t_{SA}}^{q_{SA}} = \min_{q=\{1,\ldots,N_{iterations}\}} C_t^q$;
20: $\Lambda_{SA} = \Lambda^{q_{SA}}$, $\Theta_{SA} = \Theta^{q_{SA}}$.
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Algorithm 2 Power-Coverage based User Association

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1: Input: $\Psi_k$, $c(\psi)$, $\psi \in \Psi_k$;
2: Output: $\Theta_{PoCo-UA}$;
3: Initialize $\Delta_k = \varnothing$;
4: for $k \in K$ do
5:     if $|\Psi_k| \neq 1$ then
6:         for $\psi \in \Psi_k$ do
7:             Compute $r_k^\psi = \frac{\chi_{\psi,j,k}}{\sum_{\psi \in \Psi_k} \chi_{\psi,j,k}}$, $\rho_\psi^k = \frac{c(\psi)}{\sum_{\psi \in \Psi_k} c(\psi)}$;
8:             Compute $\delta_{\psi,k} = \frac{r_k^\psi / \rho_\psi^k}{\sum_{\psi \in \Psi_k} r_k^\psi / \rho_\psi^k}$;
9:             $\Delta_k \leftarrow \Delta_k \cup \{\delta_{\psi,k}\}$;
10:        end for
11:        $\psi_k^* = Random(\Psi_k, \Delta_k) \Rightarrow \theta_{heur} = \theta_{\psi_k^*,k} = 1$;
12:    else
13:        $\psi_k^* = \{\Psi_k\} \Rightarrow \theta_{heur} = \theta_{\psi_k^*,k} = 1$;
14:    end if
15: end for
```

The complexity of executing PoCo-UA algorithm is in $\mathcal{O}(N_u \times |\Psi_k| \log |\Psi_k|)$. The complexity of executing the heuristic algorithm for the Power-Delay-Min problem (Algorithm 1) corresponds to the complexity of executing PoCo-UA at each change of the transmit power level for each BS. Hence, the complexity of Algorithm 1 is in:

$$\mathcal{O}(N_u \times |\Psi_k| \log |\Psi_k| \times N_{iterations}). \tag{11}$$

V. EXISTING APPROACHES

In this paper, we consider two existing approaches. The first approach, denoted by A_1, is based on legacy cellular networks where BSs transmit at a fixed power level and UEs are associated with the BS delivering the highest SNR [19]. Therefore, in A_1, we assume that all BSs transmit at the highest power level. In this case, all UEs are thus covered by at least one BS and they are associated with the BS delivering the highest SNR.

The second approach, denoted by A_2, is based on the existing approaches that consists in minimizing the total network power while ensuring the coverage constraint for all network UEs. It also considers the power adjustment capability of the BS as in our approach. We introduce a new parameter $\rho_{i,j,k}$ that indicates whether user k is covered by BS i transmitting at power level j. Thus, approach A_2 can be formulated as the following optimization problem $(\mathcal{P}_1)$:

$$\begin{aligned} & \underset{\Lambda}{\text{minimize}} & & C_p(\Lambda) \\ & \text{subject to} & & \end{aligned} \tag{12}$$

$$\sum_{j \in J} \lambda_{i,j} = 1, \quad \forall\ i \in I, \tag{13}$$

$$\sum_{i \in I, j \in J} \rho_{i,j,k} \cdot \lambda_{i,j} \geq 1, \quad \forall\ k \in K, \tag{14}$$

Constraints (13) state that every BS transmits only at one power level. Constraints (14) ensure that a given UE covered by at least one BS. Solving problem $(\mathcal{P}_1)$ provides the operation mode of the network BSs. For the user association, UEs are associated with the BS delivering the highest SNR.

For both approaches, the total network power, the total network delay and the total network cost are computed respectively according to (4), (5) and (6).

VI. PERFORMANCE EVALUATION

A. Evaluation Method

In order to study the efficiency of the proposed heuristic algorithm for the Power-Delay-Min problem, we implement this algorithm and compare its solution with the optimal one and the existing approaches. Based on our previous work in [13], we convert $(\mathcal{P})$ into a Mixed Integer Linear Programming (MILP) problem. The optimal solutions of both MILP and $(\mathcal{P}_1)$ problems are solved using the BB method with the CPLEX solver. We consider the realistic positioning of the 4G network BS for the district 14 of Paris-France [1]. The network topology is composed of 18 cells (N_{bs}=18) and the positioning of UEs follows a random uniform distribution, as shown in Fig. 1.

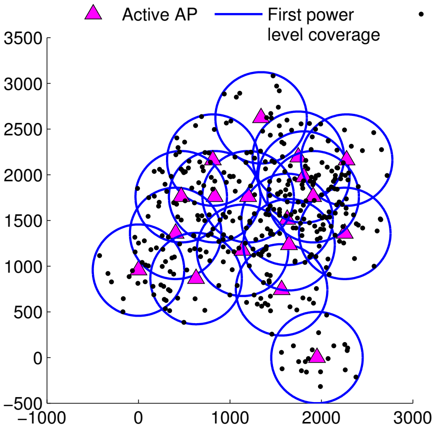


Figure 1. 4G network topology of the district 14 of Paris.

For the BS power model, we set for simplicity the number of transmit power levels to three (N_l=3). Precisely, an active BS is able to transmit at two different power levels, and when the power level equals $N_l = 3$, the BS is switched off. Moreover, we consider that the BSs are transmitting using omni-directional antennas. The simulated LTE system bandwidth is 5 MHz, therefore we have 25 RBs available in each cell. We assume a frequency reuse 3 scheme in the network to mitigate the inter-cell interference. Thus, the system bandwidth is divided into 3 equal sub-bands, each of these sub-bands are allocated to cells in a manner that no other surrounding cell is using the same sub-band. Consequently, we have 8 RBs available in each cell. The fair-time sharing model is used, and the scheduler allocates all RBs to one user at each scheduling epoch as explained in Section II-A2. Moreover, we assume a full buffer traffic model. The simulation parameters and the pathloss model follow that in [2], [3] and [4], which are summarized in Table I.

In this paper, the Path Loss (PL) between the BS and the UE is computed according to the Cost 231 extended Hata model considering a urban environment [3], with a carrier frequency f of 2000 MHz. The shadowing is represented by a random variable following normal distribution with a mean of 0 dB and a standard deviation of 10 dB.

a) Peak rate computation: Knowing the path loss, calculation of the signal strength $S_{i,j,k}$ detected by UE k from BS i transmitting at power level j is performed according to:

$$\begin{aligned} S_{i,j,k} = 10 \times \log_{10}(\pi_j \times 1000) \\ - (PL - G_T - G_R) \quad [dBm], \end{aligned} \tag{15}$$

where G_T and G_R are respectively the transmit and receiver antenna gain. The SNR detected by UE k from BS i transmitting at power level j is thus given by:

$$SNR = S_{i,j,k} - ThermalNoisePower \quad [dB]. \tag{16}$$

The thermal noise power denoted by Th_{NP} is given by:

$$\begin{aligned} Th_{NP} = 10 \times \log_{10}(1000 \times ThermalNoiseDensity \\ \times BandwidthperRB \times NumberofRBperCell) \\ + NoiseFigure \quad [dBm]. \end{aligned} \tag{17}$$

Table I
SIMULATION PARAMETERS FOR LTE

Parameter	**Value**
Input parameters of power consumption model	N_{TRX}=1, $v = 4.7$, $w_1 = w_2 = 130$ W $w_3 = 0$ W
Transmit power	π_1=10 W, π_2=5 W π_3=0
Average power consumed per BS i	$p_{i,1}$=177 W, $p_{i,2}$=153.5 W, $p_{i,3}$=0 W ($i = 1, \ldots, 18$)
Transmit antenna gain (G_T)	15 dBi
Receiver antenna gain (G_R)	0
Coverage radius for the first and the second power levels	R_1 = 500 m R_2 = 250 m
Environment	Urban
Pathloss model	Cost 231 extended Hata model
Shadowing standard deviation	10 dB
Carrier frequency	2000 MHz
Bandwidth	5 MHz
Frequency Reuse scheme	3
Number of RB per cell	8
Bandwidth per RB	180 KHz
Traffic model	Full buffer
Noise Figure	9 dB
Thermal Noise Density	-174 dBm/Hz
Thermal Noise Power (Th_{NP})	-103.4 dBm

Knowing the SNR, calculation of the spectral efficiency (in bit/s/Hz) is performed according to Fig. 2 in the 3GPP TR 36.942 [3]. As mentioned earlier, the scheduler allocates all RBs to one user at each scheduling epoch. Therefore, to compute the peak rate $\chi_{i,j,k}$ perceived by UE k from BS i transmitting at power level j in bit/s, we multiply the value obtained from Fig. 2 by the Bandwidth per RB and by the Number of RBs per cell.

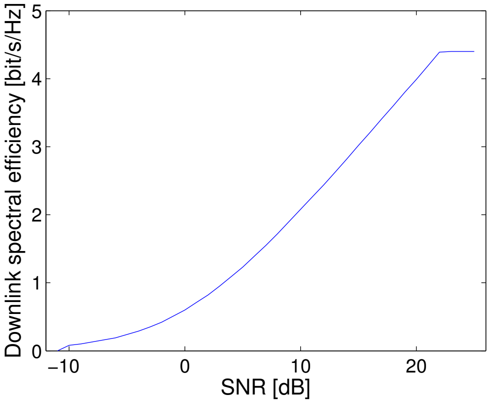


Figure 2. Spectral efficiency in LTE as a function of SNR [3].

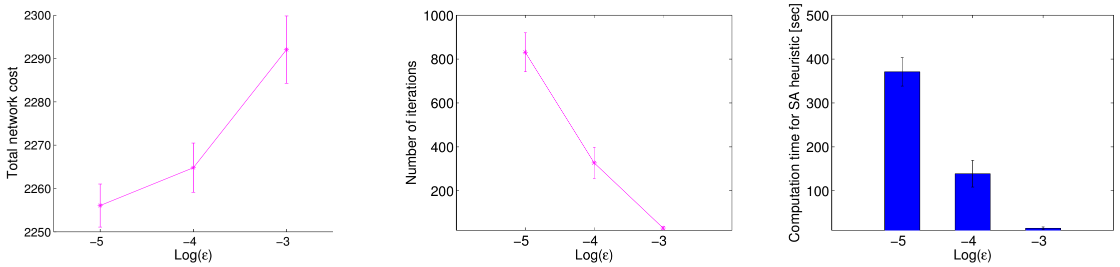
Furthermore, we only consider the case where α=β=0.5 in (7). This balances the tradeoff between minimizing power and delay. The normalization factor β' is calculated in such a way to scale the total network power and the total network delay [7]. Moreover, the user association problem is a very challenging one. Therefore, in each iteration of the heuristic algorithm, we run the PoCo-UA user association (Algorithm 2) 10 times and select the best $\theta_{PoCo-UA}$ that gives the minimal total network delay. In our SA heuristic algorithm, we take $N_{iterations}$=10^3, ϵ=10^{-4}, T=0.1. For the results of the SA heuristic, A_1 and A_2 approaches, we adopt the Monte Carlo method by generating 50 snapshots with different random uniform UE distribution. After doing the calculations for all the snapshots, we provide the 95% Confidence Interval (CI) for each simulation result. For the result of the MILP problem, we generate only two snapshots and provide the average values. This is because the large scale test scenario, the memory space limitation and the high computational complexity of the joint Power-Delay-Min problem. For the same reason, we also set a bound limit of 1200 s on the running time in the CPLEX optimization tool. The latter provides the best solution found within a given number of brand and bound iterations. It also provides the gap-to-optimality metric which expresses the gap between the obtained solution and the optimal solution estimated by the solver. In the sequel, we present the simulation results.

B. Simulation Results

Let us start by examine the cost reduction that is achieved by our SA heuristic compared with other solutions. The cost reduction is defined as follows:

$$100 \times \left(1 - \frac{\text{total network cost for the SA heuristic}}{\text{total network cost for the considered solution}}\right), \tag{18}$$

Recall that the total network cost is the sum of the total network power and the total network delay. Table II shows the percentage of cost reduction for SA heuristic compared with other solutions with variation of the number of UEs per cell. On one hand, results shows that the proposed heuristic performs very close to the optimal solution for a small number of UEs per cell (*i.e.*, $\leq$ 10). Moreover, for a high number of UEs per cell (*i.e.*, 20), the heuristic has low computational complexity whereas the optimal solution cannot be computed due to memory space limitation. It is worth mentioning that the average gap-to-optimality provided by the CPLEX splver is respectively 25.64%, 26.34% and 21.05% for 6, 8 and 10 UEs per cell. This is why, our SA heuristic provides a small positive cost reduction compared to the optimal solution. On the other hand, results shows that our heuristic outperforms A_1 with a cost reduction between 36.63 % and 24.58 % for



(a) Total network cost (b) Number of iterations (c) Computation time

Figure 3. SA heuristic results with variation of the precision parameter for 20 UEs per cell.

Table II

PERCENTAGE OF COST REDUCTION FOR SA HEURISTIC COMPARED WITH OTHER SOLUTIONS [%].

Number of UEs per cell		6	8	10	20
Optimal	Mean	0.75	1.01	1.02	-
A1	Mean	36.63	30.48	24.58	24.78
	95% CI	[35.34, 37.93]	[29.51, 31.46]	[23.86, 25.30]	[24.36, 25.20]
A2	Mean	33.73	22.05	10.07	10.35
	95% CI	[32.07, 35.39]	[20.76, 23.33]	[9.03, 11.11]	[9.33, 11.37]

all the considered number of UEs per cell. In fact, approach A_1 does not take into consideration neither saving power, nor minimizing the delay. Since in this approach all BSs transmit at the highest power level, and UEs are associated according to Po-UA, A_1 solution has the highest total network cost for a given number of UEs per cell. Thus, the highest the cost reduction is for our SA heuristic compared with A_1 solution for a given number of UEs per cell. Moreover, our heuristic also outperforms A_2 with a cost reduction between 33.73 % and 10.07% for all the considered number of UEs per cell. In A_2, the aim is to minimize only the total network power which is one component of the total network cost and ensure coverage for all UEs in the network. Thus, A_2 approach does not take into account the delay minimization. However, in our SA heuristic, our aim is to minimize simultaneously the total network power and the total network delay.

Table III

PERCENTAGE OF POWER SAVING [%] AND DELAY REDUCTION [%] FOR SA HEURISTIC COMPARED WITH A_1 AND A_2 SOLUTIONS FOR 20 UES PER CELL.

(a) Power saving

A1	Mean	18.28
	95% CI	[17.08, 19.48]
A2	Mean	-17.07
	95% CI	[-18.99, -15.15]

(b) Delay reduction

A1	Mean	31.99
	95% CI	[30.24, 33.74]
A2	Mean	31.53
	95% CI	[29.24, 33.81]

We consider the case where we have 20 UEs per cell, and we show in Table III the power saving and the delay reduction that are achieved by our solution compared with A_1 and A_2 solutions. The power saving and the delay reduction are computed as in (18) but we replace the total network cost by respectively the total network power and the total network delay. Compared with A_1, results show that our SA heuristic provides power saving of up to 18 % and delay reduction of up to 32 %. The cause of power saving in our SA heuristic comes from switching off some BS and adjusting the transmit power of others. Moreover, the cause of delay reduction is that our heuristic associate UEs with the network BS in such a way to minimize the total network delay. Therefore, approach A_1 which is equivalent to legacy networks waste the power without enhancing the delay. In comparison with A_2, the power saving is -17% while the delay reduction is up to 31 %. In fact, in A_2 the percentage of switched-off BS and the percentage of BS transmitting at low power level are respectively 29.56 % and 4.22 %. However, in our heuristic, the former equals 16.11 % and the latter equals 16.33 %. On one hand, This explains why the power saving in this case is negative. On the other hand, with a high percentage of switched-off BS, the total network delay increases. Therefore, approach A_2 minimizes the total network power in the detriment of total network delay increase. Consequently, minimizing only the total network power while ensuring covering for UEs in the network, can no longer be considered alone. Further, our SA heuristic balances the tradeoff between minimizing the power and delay.

Considering also the case where we have 20 UEs per cell, we vary the value of the precision parameter in our SA heuristic algorithm. We plot in Fig. 3 the total network cost, the number of iterations of the heuristic algorithm and its computation time as a function of the log of the precision parameter. Figure 3(a) shows that we obtain the lowest total network cost for the lowest simulated value of ϵ (*i.e.*, 10^{-5}), and as ϵ decreases the total network cost decreases. Moreover, Figure 3(b) shows that with small values of ϵ, the number of algorithm's iterations increases. This also increases the computation time of the algorithm as shown in Fig. 3(c). In our simulations, we choose $\epsilon = 10^{-4}$ providing solution near to the optimal one with a very moderate time and iterations.

VII. CONCLUSION

In this paper, we developed a joint Power-Delay minimization problem in LTE networks. Due to the high computational complexity to obtain the optimal solution, we proposed a novel SA based heuristic algorithm for this problem. Our goal was to come-up with a large-scale heuristic that has low computational complexity and that reduces the total network cost. We evaluated our SA algorithm on the realistic 4G network in Paris-France. Simulation results showed that the proposed heuristic performs close to the optimal and outperforms existing approaches in terms of cost reduction. Moreover, for large number of UEs in the network, the optimal solution is intractable whereas the heuristic algorithm provides efficient results in a reasonable time. Furthermore, compared with legacy solutions, our heuristic provides power saving of up to 18% and delay reduction of up to 32%. Thus, it balances the tradeoff between minimizing the power and delay. In future work, we plan to study the joint Power-Delay-Min problem in heterogeneous networks. Thus, we will study the case of macro BS integrated with WLAN access points located in different hotspots in the network area.

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