Performance of Green LTE Networks Powered by the Smart Grid with Time Varying User Density

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***Abstract*—In this study, we implement a green heuristic algorithm involving the base station sleeping strategy that aims to ensure energy saving for the radio access network of the 4G-LTE (Fourth Generation Long Term Evolution) mobile networks. We propose an energy procurement model that takes into consideration the existence of multiple energy providers in the smart grid power system (e.g. fossil fuel and renewable energy sources, etc.) in addition to deployed photovoltaic panels in base station sites. Moreover, the analysis is based on the dynamic time variation of daily traffic and aims to maintain the network quality of service. Our simulation results show an important contribution in the reduction of CO_2 emissions that can be reached by optimal power allocation over the active base stations.**

***Index Terms*—Green communication, procurement model, energy saving, sleeping strategy, smart grid.**

I. Introduction

Due to the exploding use of wireless mobile applications, a notable increase in energy consumption causes more and more harmful impact on the environment and makes Information and Communication Technologies (ICTs) a major contributor to overall greenhouse gas emissions [1]. In fact, 2-4% of total carbon dioxide emissions come from the ICT industry with a large contribution of Base Stations (BSs) [2]. It is well known that idle BSs consumes more than 50% of the energy due to circuit processing, air conditioning and other factors [3]. To cope with this, several strategies have been proposed to improve energy efficiency of mobile networks and exploit their load variation and idle periods by shutting down not fully loaded BSs. The energy efficiency of the BS sleeping strategy has been widely explored in literature [4], [5], [6] and many algorithms have been proposed to reduce the number of active BSs depending on different criteria which are themselves based on different Quality of Service (QoS) metrics. However, most of these works do not analyze the performance of this strategy in the time domain. In fact, they are limited to snapshot realizations where the number of users is considered fixed and the channel evolution is ignored. Nevertheless, recent works [7], [8] propose several BS sleeping schemes and investigate their daily performance. The proposed approaches operate every long periods of time based on average traffic models. Thus, the switch-offs becomes unaccommodated to the instantaneous user variation and the network becomes unprotected from QoS degradation risk. On the other hand, another way to ensure energy saving is to exploit the advantages of the modern electrical system: Smart Grid (SG) [9]. Thanks to its capability to integrate intermittent renewable resources and its automated fashion to improve the efficiency, reliability and sustainability of the production and distribution of electricity, SG offers several positive benefits to the environment. Indeed, it increases the opportunity to purchase energy from clean resources, further creating a demand for the shift from a carbon-based to a green economy [10].

In [6], we presented a snapshot based solution for green LTE networks powered by the smart grid. In this study, we propose an algorithm and analyze the performance during continuous operation of the network as the user traffic and the available renewable energy vary dynamically. Indeed, the objective of this work is to optimize the continuous BS sleeping operation and the SG energy procurement of LTE mobile networks through time to ensure green objectives without affecting the required QoS. The behavior of the network becomes dependent on several parameters such as the time of the day (peak hours, late night, etc.), user density and energy availability in green generators deployed in BS sites and in the multiple energy providers existing in the SG.

The rest of this paper is organized as follows. Section II presents the system model. Section III describes the problem formulation. The green iterative algorithm is developed in Section IV. In Section V, we present our simulation results. Finally, the paper is concluded in Section VI.

II. System Model

We consider a uniform geographical area where an LTE network is deployed. The area is divided into cells of equal size where a BS is placed in the center of each cell. In LTE, the access scheme for the DownLink (DL) is the Orthogonal Frequency Division Multiple Access (OFDMA) while in the UpLink (UL) the Single Carrier Frequency Division Multiple Access (SC-FDMA) is used. In fact, the available spectrum is divided into $N_{\mathrm{RB}}^{(\mathrm{DL})}$ Resource Blocks (RB) that contain a fixed number of consecutive subcarriers. RBs are assigned to users according to the resource allocation procedure described in [4].

A. Power Consumption Model for Base Stations

We consider that each BS is equipped with a single omni-directional antenna. The consumed power of a switched on BS

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j, P_j^{BS}, can be computed as follows [11]:

$$P_j^{BS} = aP_j^{tx} + b, \tag{1}$$

where the coefficient a corresponds to the power consumption that scales with the radiated power due to amplifier and feeder losses and the term b 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 (1), P_j^{tx} denotes the radiated power of the j^{th} BS and can be expressed as follows:

$$P_j^{tx} = \sum_{r=1}^{N_{\text{RB}}^{(\text{DL})}} P_r, \tag{2}$$

where P_r is the power consumed per one RB and depends on the RB state. If the RB r of BS j is allocated to a certain user, then $P_r = \frac{P_{tot}}{N_{\text{RB}}^{(\text{DL})}}$ else $P_r = P_{idle} \approx 0.19$ dBm, [12]. If a BS j is completely switched off, we assume that its power consumption $P_j^{BS} = 0$.

B. Retailers and Pollutant Levels

In our study, we assume that the cellular network is powered by a SG where N retailers exist. Each retailer is characterized by an offered unitary price and a pollutant level depending on the nature of the generated energy. The mobile operator has to procure from each retailer n ($n = 1 \cdots N$) a certain amount of energy $q_j^{(n)}$ for each BS j. The procurement decision mainly depends on two factors: the unitary price of the provided energy $\pi^{(n)}$ and the penalty term related to pollutant emission of the energy source which is described by a quadratic function of the power consumed during a period Δt as follows [13]:

$$F(q_j^{(n)}) = \alpha_n \left(\frac{q_j^{(n)}}{\Delta t} \right)^2 + \beta_n \frac{q_j^{(n)}}{\Delta t}, \tag{3}$$

where α_n and β_n are the emission coefficient of retailer n. Also, we suppose that each retailer n has to provide at most $Q_{\max}^{(n)}$ of energy for the network. $\left(\text{i.e. } \sum_{j=1}^{N_{\text{BS}}} q_j^{(n)} \leq Q_{\max}^{(n)}\right)$.

The network can also procure energy from renewable energy equipment deployed in BS sites. In fact, each BS would be powered by its own installed equipment, e.g. solar cells or wind turbine. The auto-generated amount of energy by BS j is denoted $q_j^{(0)}$. In addition, we suppose that all BSs have the same maximum capacity to store the produced energy denoted $Q_{\max}^{BS}$ and depending on the generator yield, the available green energy at BS j is denoted $Q_{\text{RE}_{\max}}^{(j)}$ where $q_j^{(0)} \leq Q_{\text{RE}_{\max}}^{(j)} \leq Q_{\max}^{BS}$ $\forall j = 1 \cdots N_{\text{BS}}$. To summarize, we distinguish two notations of the procured energy:

- $q_j^{(n)}$ is the amount of energy provided for BS j and bought from retailer n.
- $q_j^{(0)}$ is the amount of renewable energy generated locally in BS j site and is free of charge.

C. Photovoltaic Model

In our study, we assume that the green energy that is generated locally in BS sites corresponds to the Photovoltaic (PV) energy. The hourly behavior of the solar radiation is an important parameter that impacts on the generated energy yield. In fact, the solar rating depends essentially on the size of PV panels and whether they experience any shading during the day. Several works have been proposed to model the solar radiation. One of these works [14] presents it as a mathematical model where the hourly variations fit to Gaussian shapes and gives a global view of the solar radiation phenomenon by involving the day and night period. The Gaussian model is expressed as follows:

$$G(t) = \frac{A\, e^{-(t-B)^2}}{C^2}, \tag{4}$$

where A corresponds to the height of the Gaussian peak which refers to the maximum power that can be generated, B is the position of the peak and C is related to the shape width at half maximum of the peak.

D. Operator Services and User Arriving Process

In our framework, we consider that the network operator offers M different services to its subscribers. Each service is characterized by data rate thresholds $R_{m,th}^{(\text{UL})}$ and $R_{m,th}^{(\text{DL})}$ for UL and DL, respectively, and a unitary price $p^{(m)}$ with $m = 1 \cdots M$. We suppose that each user in the network benefits from one of the M offered services and has its random call duration. In fact, in our study, we model mobile calls as log-normal or Weibull distributions [15] depending on the chosen services and the activity of subscribers (i.e. personal call or business call). Concerning the traffic arrival, we consider that the daily traffic pattern of the network can be approximated by a sinusoidal profile close to practical patterns [16] as follows:

$$\Psi(t) = \frac{1}{2^d} \left[1 + sin\left(\frac{\pi t}{12} + \phi \right) \right]^d + n(t), \tag{5}$$

where $\Psi(t)$ is the instantaneous normalized traffic, ϕ is a uniform random variable in the interval $[0, 2\pi]$ and determines the distribution of traffic pattern, $n(t)$ is a Poisson distributed random process which models random fluctuations of the total traffic; and $d = 1$ or 3 determines the abruptness of the traffic profile. Note that with $d = 3$ the curve has a steeper slope [16]. This model takes into account peak hours and reduces the number of users at night.

III. Problem Formulation

Based on the models presented in Section II, we formulate a unique optimization problem that encloses all these parameters in order to achieve an environmentally friendly objectives. In our time driven approach, we consider that N_{BS} BSs are deployed in the area of interest. We denote by N_{out} the number of users in outage during a period Δt ($N_{\text{out}} \ll N_U$) where N_U is the number of users connected to the network at instant Δt. A user i using the m^{th} service communicates successfully with a BS, if its UL and DL data rates during Δt, denoted $R_i^{(\text{UL})}$ and $R_i^{(\text{DL})}$, are higher than the service data rate thresholds, $R_{m,th}^{(\text{UL})}$ and $R_{m,th}^{(\text{DL})}$ respectively. As the user data rates depend on the channel variation, we assume that the user connection to network is broken, if, at any instant of the communication, the data rate condition is not satisfied. By denoting a binary parameter γ_i, $i = 1 \cdots N_U$, we can express this assumption as follows:

$$\gamma_i = \begin{cases} 1 \text{ if } R_i^{(\mathrm{UL})} \geq R_{m,th}^{(\mathrm{UL})} \text{ and } R_i^{(\mathrm{DL})} \geq R_{m,th}^{(\mathrm{DL})}, \\ 0 \text{ if } R_i^{(\mathrm{UL})} < R_{m,th}^{(\mathrm{UL})} \text{ or } R_i^{(\mathrm{DL})} < R_{m,th}^{(\mathrm{DL})}. \end{cases} \quad (6)$$

In other words, if $\gamma_i = 0$, the i^{th} user is in outage during Δt. Let the vector $\boldsymbol{\gamma} = [\gamma_1 \cdots \gamma_{N_U}]$, then the number of ones and the number of zeros in $\boldsymbol{\gamma}$ correspond to the number of served users and the number of users in outage, respectively. Consequently, only the served users pay the equivalent of the proposed service. Hence, the operator network revenue $\mathcal{R}$ corresponding to the exploitation of its offered services is expressed as follows:

$$\mathcal{R}(\boldsymbol{\gamma}) = \sum_{i=1}^{N_U} \gamma_i p_i^{(m)}, \quad (7)$$

where $p_i^{(m)}$ is the unitary cost of the service m used by the i^{th} user. On the other hand, in order to include the BS sleeping strategy in the problem formulation, we introduce a binary variable ϵ_j with $j = 1 \cdots N_{\mathrm{BS}}$ to denote the BS state during a certain period Δt. If BS j is switched on, $\epsilon_j = 1$, else, $\epsilon_j = 0$. Let $\boldsymbol{\epsilon} = [\epsilon_1 \cdots \epsilon_{N_{\mathrm{BS}}}]$. The number of ones and the number of zeros in this vector indicate the number of active and inactive BSs, respectively.

Each BS can be powered by the auto-generated energy in its BS site and/or by N public retailers available in the SG as detailed in Section II-B. Each retailer is assumed to generate electricity form a different energy source. Hence, we can have retailers generating electricity from renewable energy sources, and others generating electricity from fossil fuels. Therefore, if the self-generated renewable energy is not enough to cover the need of all BSs, the network operator can procure additional energy from public retailers existing in the SG that have a sufficient amount of energy. Depending on the procured fossil fuel, the CO_2 emission caused by electricity generation may differ and the pollution caused to the environment would vary. The pollution caused by the cellular network during Δt depends only on the energy consumption of the switched on BSs (i.e. $\boldsymbol{\epsilon}$) and, of course, the nature of the procured energy. The function $\mathcal{I}$, expressed in the following, reflects the friendliness of the network operator to the environment and corresponds to the CO_2 emission penalty function of the network:

$$\mathcal{I}(\boldsymbol{\epsilon}, \boldsymbol{q}) = \sum_{j=1}^{N_{\mathrm{BS}}} \sum_{n=1}^{N} \epsilon_j \left(\alpha_n \left(\frac{q_j^{(n)}}{\Delta t} \right)^2 + \beta_n \frac{q_j^{(n)}}{\Delta t} \right), \quad (8)$$

where $\boldsymbol{q} = [q_1^{(0)} \cdots q_{N_{\mathrm{BS}}}^{(N)}]^T_{1 \times (N_{\mathrm{BS}} \times (N+1))}$ is the vector that contains the procured energy amount by the j^{th} BS from the n^{th} energy source. On the other hand, retailers propose different unitary prices depending on the availability of the produced power. For instance, public green retailers produce a limited energy which will be distributed and shared by several infrastructures; among them, the network in the area of interest. Prices can also vary from a retailer to another depending on the demand and supply economic theory. Consequently, the total cost of the energy consumption of the cellular network $\mathcal{C}$ is given by:

$$\mathcal{C}(\boldsymbol{\epsilon}, \boldsymbol{q}) = \sum_{j=1}^{N_{\mathrm{BS}}} \sum_{n=1}^{N} \epsilon_j \pi^{(n)} q_j^{(n)}, \quad (9)$$

where $\pi^{(n)}$ is the cost of one kWh of energy provided by the n^{th} retailer ($n = 1, \cdots, N$). Given these functions, the mobile operator has to optimally compute the amount of energy to procure from retailers existing in the SG and from generators installed in BS sites in order to maximize the following multi-objective utility function at each period of time Δt:

$$U = \mathcal{P}(\boldsymbol{\gamma}, \boldsymbol{\epsilon}, \boldsymbol{q}) - \mathcal{I}(\boldsymbol{\epsilon}, \boldsymbol{q}), \quad (10)$$

where $\mathcal{I}(\boldsymbol{\epsilon}, \boldsymbol{q})$ is given in (8) and $\mathcal{P}(\boldsymbol{\gamma}, \boldsymbol{\epsilon}, \boldsymbol{q}) = \mathcal{R}(\boldsymbol{\gamma}) - \mathcal{C}(\boldsymbol{\epsilon}, \boldsymbol{q})$ is the function that corresponds to the mobile operator's profit. It should be noted that the amount of energy produced by BS generators ($q_j^{(0)}$ for $j = 1, \cdots, N_{\mathrm{BS}}$) are not included in the cost and CO_2 emission penalty function as these green consumed energies are free of charge for the operator and do not pollute the environment. Hence, the optimization problem that will be solved every Δt is expressed as follows:

$$\underset{\boldsymbol{\gamma}, \boldsymbol{\epsilon}, \boldsymbol{q}}{\text{Maximize}} \; U = \mathcal{P}(\boldsymbol{\gamma}, \boldsymbol{\epsilon}, \boldsymbol{q}) - \mathcal{I}(\boldsymbol{\epsilon}, \boldsymbol{q}), \quad (11)$$

$$\text{S.t.: } \sum_{j=1}^{N_{\mathrm{BS}}} \epsilon_j q_j^{(n)} \leq Q_{\max}^{(n)}, \; \forall n = 1, \cdots, N, \quad (12)$$

$$q_j^{(0)} \leq Q_{\mathrm{RE}_{\max}}^{(j)}, \; \forall j = 1, \cdots, N_{\mathrm{BS}}, \quad (13)$$

$$\sum_{n=0}^{N} q_j^{(n)} = P_j^{BS} \Delta t, \; \forall j = 1, \cdots, N_{\mathrm{BS}}, \quad (14)$$

$$\frac{N_{\mathrm{out}}}{N_U} \leq P_{\mathrm{out}}, \quad (15)$$

$$q_j^{(n)} \geq 0, \; \forall j = 1 \cdots N_{\mathrm{BS}} \text{ and } , \forall n = 0, \cdots, N. \quad (16)$$

The constraint (12) indicates that the energy consumed by all BSs in the cellular network from retailer n cannot exceed the total energy that can be provided by that retailer during Δt while (13) indicates that the energy procured by a BS j from its auto-produced energy cannot exceed the amount of energy that can be stored, (14) indicates that the amount of energy drawn by a BS from all retailers and from the renewable energy generated locally should be equal to the energy needed for its operation during that period, (15) forces the number of users in outage to be less than a tolerated outage probability threshold P_{out}, and (16) is a trivial constraint expressing the fact that the energy drawn is a positive amount. It should be noted that, when a certain retailer n can provide for the mobile network operator enough electricity to power all the BSs in the network, we can set $Q_{\max}^{(n)} = +\infty$ to relax the constraint (12) for that retailer, although in practice the amount of energy produced is naturally finite.

IV. Green Algorithm

In our approach, we propose to solve the optimization problem formulated in Section III periodically in order to optimize the energy procurement from the SG and switch off underutilized BSs according to the system parameters (i.e.

channel conditions, available amount of renewable energy and number of subscribers connected to the network). For this reason, a periodic computation has to be performed to find the best combination of $\boldsymbol{\gamma}$, $\boldsymbol{\epsilon}$ and $\boldsymbol{q}$ at each period denoted T. However, since the two decision variables $\boldsymbol{\gamma}$ and $\boldsymbol{\epsilon}$ are binary variables, the problem formulated in (11) is considered as a combinatorial problem which makes the optimal and exact solution difficult or even impossible to find [17]. Therefore, we employ a heuristic approach where, at each period T, we try to find the best BS combination that maximizes the utility function expressed in (10) by successively eliminating a BS after another. During each period T, the system parameters are updated as follows:

- User distribution: New users could connect to the network according to the arrival process described in Section II-D while other users could disconnect for two reasons: the call duration takes end or the QoS associated to the call is not satisfied. Although the algorithm is repeated each T, users can connect anytime, i.e. they do not have to wait to get a service. They can connect to one of the active BSs, and then they can be handed over to another one, if needed, once the algorithm is executed.
- Renewable energy availability: Renewable energy generated locally can increase or decrease following the model presented in Section II-C and depending on the BS power consumption.
- Channel conditions: The variation of the channel parameters due to fading and shadowing has an important impact on the QoS of UL and DL. In fact, in some cases, users can be obliged to switch their connection from one BS to another (Handover).

At each iteration, the algorithm switches off the BS that when eliminated offers the highest utility U and satisfies the QoS at the same time. It converges when none of the active BSs can be turned off.

Consider N_{BS} BSs deployed in a given area and forming a set $\mathcal{S}$. Initially, we assume all BSs are switched on (i.e. $\boldsymbol{\epsilon} = [1 \cdots 1]$). We consider also N_U users are connected during this period T to benefit from the operator network services. As a first step, the algorithm computes the data rates of all users and compares them to the data rate thresholds after applying the resource allocation algorithm described in details in [4]. By this way, it identifies the users in outage N_{out} and consequently the value of the vector $\boldsymbol{\gamma}$. Once both vectors $\boldsymbol{\epsilon}$ and $\boldsymbol{\gamma}$ are known and fixed, the optimization problem formulated in (11) becomes a quadratic concave optimization problem that has a unique optimal solution and depends only on one decision variable: the vector $\boldsymbol{q}$. Next, we initialize the optimal utility function as the initial maximum utility $U_{\max} = U(\tilde{\boldsymbol{q}}) = \mathcal{P}(\tilde{\boldsymbol{q}}) - \mathcal{I}(\tilde{\boldsymbol{q}})$, where $\tilde{q}_j^{(n)}$ are the elements of the optimal vector $\tilde{\boldsymbol{q}}$. Then, we eliminate successively one BS and compute the corresponding optimal utility function U_j and we compare $\max_j(U_j)$ to the previous utility $U_{\max}$ to decide whether eliminating BSs is possible or not. We repeat the same procedure as performed previously but with a reduced number of BSs. Details of the proposed method are presented in Algorithm 1.

The choice of T would vary in time according to the need of the mobile operator. For instance, if the traffic variation is slow (during night), the mobile operator can increase T, e.g $T = 1$ hour. However, if the traffic variation is relatively fast, the execution period can be decreased to maintain the required QoS, e.g. $T = 1$ minute.

Algorithm 1 Iterative Algorithm for Green Procurement

loop
- Compute the utility function $U_{\max}$ when all BSs are switched on ($\mathcal{S}$ contains all BSs and $\boldsymbol{\epsilon} = [1 \cdots 1]$) and initialize the current iteration with $\mathcal{S}^{\text{iter}} = \mathcal{S}$ and $N_{\text{BS}}^{\text{iter}} = N_{\text{BS}}$.
- Set $U_{k_{\text{op}}}^{\text{new}} = U_{\max}$.
while $U_{k_{\text{op}}}^{\text{new}} \geq U_{\max}$ **do**
for $k = 1$ to $N_{\text{BS}}^{\text{iter}}$ **do**
- Eliminate BS k from $\mathcal{S}^{\text{iter}}$ ($\boldsymbol{\epsilon}^{(k)} = [1 \cdots 1 \underbrace{\overbrace{0}}_{k^{th} position} 1 \cdots 1]$).
- Allocate resources (Select serving BS and UL and DL RBs) to all users and compute $\boldsymbol{\gamma}^{(k)}$ for the iteration k as shown in (6).
if $\frac{N_{\text{out}}}{N_U} \leq P_{\text{out}}$ **then**
- Find $\tilde{\boldsymbol{q}}$ by solving the quadratic optimization problem formulated in (11) given $\boldsymbol{\epsilon}^{(k)}$ and $\boldsymbol{\gamma}^{(k)}$.
- Compute the utility function corresponding to the k^{th} iteration: U_k for the optimal value $\tilde{\boldsymbol{q}}$ as given in (10).
else
- BS k can not be eliminated (we set $U_k = -\infty$).
end if
end for
- Find the BS k_{op} that, when eliminated, provides the highest utility ($U_{k_{\text{op}}}^{\text{new}} = \max_k U_k$).
if $U_{k_{\text{op}}}^{\text{new}} \geq U_{\max}$ **then**
- BS k_{op} is eliminated.
- $\mathcal{S}^{\text{iter}} = \mathcal{S}^{\text{iter}} \setminus \{k_{\text{op}}\}$, $N_{\text{BS}}^{\text{iter}} = N_{\text{BS}}^{\text{iter}} - 1$ and $U_{\max} = U_{k_{\text{op}}}^{\text{new}}$.
end if
end while
- No more changes can be made and the final optimal set of active BSs during T is $\mathcal{S}^{\text{iter}}$.
- Update time T and the traffic and identify the N_U users connected to the network.
- Update channels and the auto-generated PV amounts.
end loop

V. Results and Discussion

In this section, we investigate the performance of the proposed algorithm and the procurement model presented in Section III and Section IV.

A. Simulation Model

We consider a 4×4 (Km^2) LTE coverage area where $N_{\text{BS}} = 16$ BSs are placed uniformly according to the cell radius, selected to be 0.5 km. The LTE and channel parameters are obtained from [12]. All BSs and all MSs have the same power model and the same maximal transmit power, respectively. These parameters are detailed in Table I. In addition, we suppose that the network operator offers $M = 3$ different services. Each one is characterized by its cost (unitary price) $p^{(m)}$, expressed in Monetary Units (MU), DL and UL data rate thresholds ($R_{m,th}^{(\mathrm{DL})}$ and $R_{m,th}^{(\mathrm{UL})}$ respectively), the mobile call model and the occurrence probability of the service as shown in Table II. The occurrence probability of a given service corresponds to the percentage of users in the network using that service. It varies depending on call natures and the current time: 80% of the calls are assumed to be business calls during working hours while 70% of the calls during non working hours are considered as personal calls. Concerning the energy providers, we assume that $N = 2$ retailers are available in the SG to produce energy from different sources. Each type of energy source n is characterized by a unitary price $\pi^{(n)}$, a total available energy $Q_{\max}^{(n)}$, and two pollutant coefficients α_n and β_n as showed in Table III. We suppose that the second retailer is engaged to provide for the network a limited amount of energy $Q_{\max}^{(2)} = 4$ kWh during the whole day (day and night): for instance, it can correspond to a renewable energy provider producing electricity from wind or solar energy. In addition, we assume that the network operator has deployed its own solar panels in BS sites to produce clean and free of charge energy. The available energy per BS j at any instant of the day, $Q_{\mathrm{RE}_{\max}}^{(j)}$, can not exceed the storage capacity and the maximum amount of the auto-generated green energy cannot exceed 1.8 kWh per one BS when favorable conditions exist.

B. Simulation Results

In our simulation, we initialize our algorithm by assuming that $N_U = 10$ users are connected to the network with random call durations. In our case, the starting instant corresponds to midnight (0:00 am). We run the simulation for 48 hours (2 days) according to the arrival process given in (5) and we analyze two scenarios: the first scenario entitled traditional (or trad.) refers to the case when all BSs are kept activated and powered by the SG and local equipment while the second scenario (prop.) corresponds to the case when BS sleeping strategy is applied using the green algorithm presented in Section IV. In addition, we employ our heuristic algorithm every $T = 1$ minute after updating user connection and energy amounts. We investigate the performance of the schemes by considering pathloss and shadowing. Fading analysis is left for a future work.

As a first step, we start by studying the impact of the green algorithm on the mobile operator's profit in addition to the total energy consumption of the network. Clearly, Fig.1 shows a strong relationship between the user behavior during 24-hours, the total consumed energy and the corresponding profit. In fact, the higher is the number of users, the higher is the network energy consumption. However, thanks to the application of the BS sleeping strategy, the network operator is able to ensure energy saving by switching off redundant BS mainly during non-peak hours with offering a significant gain in terms of profit during this period comparing to the traditional case. For instance, the proposed scheme can ensure a reduction of 80% of the total energy consumed, thus of CO_2 emissions, between 22 pm and t=6 am of the second day.

TABLE I
CHANNEL AND POWER PARAMETERS

Parameter	Value	Parameter	Value
Pathloss constant (dB)	-128.1	Pathloss exponent	3.76
Shadowing deviation (dB)	8	P_{out}	0.02
$(B^{(\mathrm{DL})}, B^{(\mathrm{UL})})$ (MHz)	$(10, 10)$	$(N_{\mathrm{RB}}^{(\mathrm{DL})}, N_{\mathrm{RB}}^{(\mathrm{UL})})$	$(50, 50)$
BS Tx power (W)	10	MT Tx power (W)	0.125
a	7.84	b (W)	71.5

TABLE II
SERVICE PARAMETERS

Services	Service 1	Service 2	Service 3
$p^{(m)}$ (MU/s)	0.01	0.005	0.002
$(R_{m,th}^{(\mathrm{DL})}, R_{m,th}^{(\mathrm{UL})})$ (kbps)	$(1000, 384)$	$(384, 384)$	$(64, 64)$
Occurrence Probability			
(Personal call)	0.1	0.2	0.7
(Business call)	0.1	0.3	0.6
Call model	Weibull	Weibull	Log-normal

TABLE III
ENERGY PROVIDER PARAMETERS

Retailers	Retailer 1	Retailer 2
$\pi^{(n)}$ (MU/kWh)	0.1	0.2
$Q_{max}^{(n)}$ (kWh)	$+\infty$	5
(α_n, β_n)	$(0.02, 0.2)$	$(0, 0)$

In Fig.2, we analyze the consumption of the three energies that power the network: electricity and renewable energy procured from the SG in Fig.2(b) and Fig.2(c), respectively, and the solar energy generated locally by the network equipment as showed in Fig.2(a). The energy procurement depends essentially on the availability of the locally generated green energy. In fact, during its absence, the environmentally friendly network operator consumes in priority the green energy procured from the SG then it compensates the lack of renewable energy by procuring electricity which corresponds to the pollutant energy that contributes in the emissions of greenhouse gas. However, when the local renewable energy is available, the network operator is able to power its network without requiring additional power from the SG. Furthermore, we notice that the BS sleeping strategy can help in the reduction of CO_2 emissions by offering the possibility to consume green energy for a longer time period. In fact, with the proposed scheme, solar energy can be consumed for 1 to 4 additional hours. Using the BS sleeping strategy, we were able to reduce the consumption of the pollutant energy by procuring only green energy most of the time as showed in Fig.2(b).

These results are confirmed in Fig.3(a) where we compute the number of active BSs during the two days after applying the proposed green algorithm. We notice that, at peak hours, 15-16 BSs are activated to serve all subscribers while at night and off-peak hours, the active BS number is reduced to 1 or 2 BSs. Between these periods, more BS are activated or deactivated depending on the number of subscribers connected to the network. In order to consume a low amount of power, the green algorithm tries, gradually, to switch on the minimum

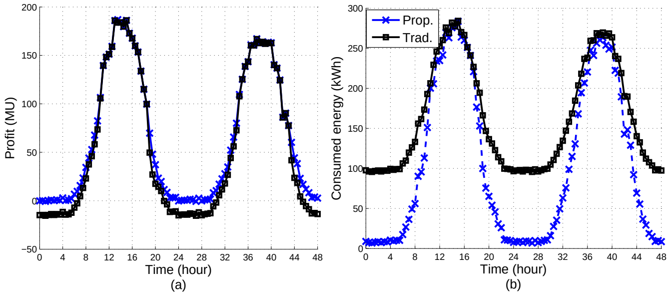

Fig. 1. Performance of the proposed scheme: (a) Profit of the mobile network (b) Total energy consumption of the network.

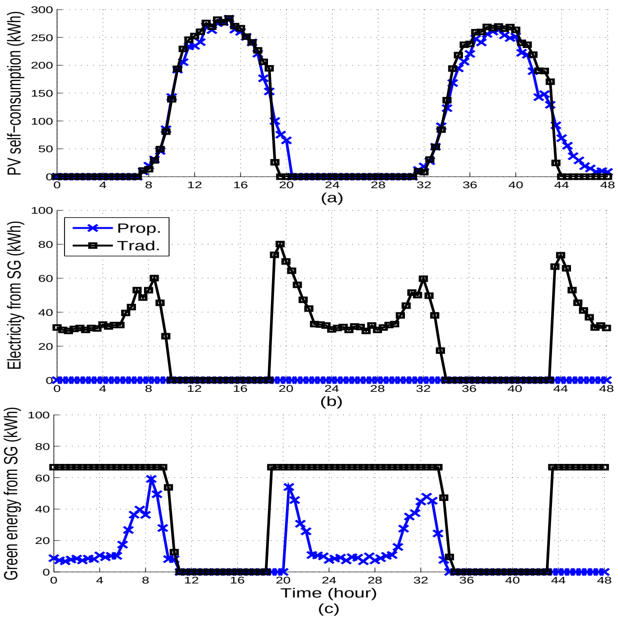

Fig. 2. Amount of energies procured from the SG and from local equipment (a) Electricity procured from the SG (b) Solar energy consumed by the network (c) Green energy procured from the SG.

number of BSs that respects the QoS mentioned in Table I. For this reason, we notice, from Fig.3(b), a high number of users in outage between 7:00 am and 10:00 am and 19:00 pm and 21:00 pm of each day. However, during peak hours, the outage percentage becomes lower because the network operator is obliged to activate all BSs to serve the high number of subscribers. During non-peak hours, the outage percentage is close to 0 due to the low number of connected users.

VI. Conclusions

In this paper, we investigated the performance of the proposed procurement model and the green iterative algorithm that ensure energy savings and greenhouse gas emission reduction for LTE networks by solving a multi-objective optimization problem. This is achieved by eliminating redundant BSs and by optimally procuring energy from the SG and from private green energy equipment without affecting the network QoS. In our future work and in order to get more practical results, we will focus on improving our proposed algorithm by taking into account previous BS state modes (idle or active) in our problem constraints and by modeling the power consumption during the switching operation from sleep to active mode and vice-versa.

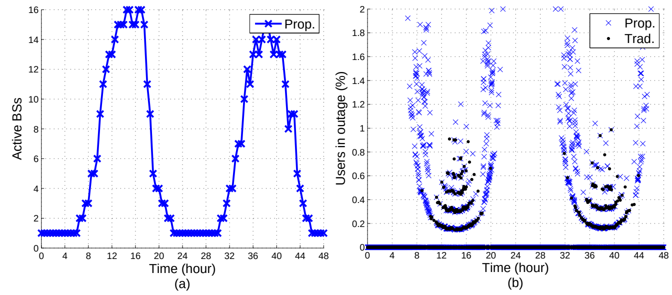

Fig. 3. Daily strategy of the proposed algorithm (a) Number of active BSs (b) Percentage of users in outage

References

[1] "Smart 2020: Enabling the low carbon economy in the information age," in *The Climate Group, Globe e-Sustainability Initiative (GeSI)*, 2008.

[2] Parliament Office of Science and Technology, "ICT and CO_2 Emmissions," tech. rep., 2008.

[3] J. Louhi, "Energy efficiency of modern cellular base stations," in *Proc. of the 29th International Telecommunications Energy Conference, (INTELEC 2007)*, pp. 475–476, Rome, Italy, Oct. 2007.

[4] E. Yaacoub, "Performance study of the implementation of green communications in LTE networks," in *Proc. of the 19th International Conference on Telecommunications (ICT 2012)*, Jounieh, Lebanon, Apr. 2012.

[5] W. El-Beaino, A. M. El-Hajj, and Z. Dawy, "A proactive approach for LTE radio network planning with green considerations," in *Proc. of the 19th International Conference on Telecommunications (ICT 2012)*, Jounieh, Lebanon, Apr. 2012.

[6] H. Ghazzai, E. Yaacoub, M.-S. Alouini, and A. Abu-Dayya, "Optimized green operation of LTE networks in the presence of multiple electricity providers," in *Proc. IEEE International Workshop on Emerging Technologies for LTE-Advanced and Beyond-4G in conjunction with IEEE Global Communications Conference (Globecom 2012)*, Anaheim, CA, USA, Dec. 2012.

[7] A. Bousia, E. Kartsakli , L. Alonso and C. Verikoukis, "Dynamic energy efficient distance-aware base station switch On/Off scheme for LTE-Advanced," in *Proc. of the IEEE Global Telecommunications Conference (GLOBECOM 2012)*, Anaheim, CA, USA, Dec. 2012.

[8] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Multiple daily base station switch-offs in cellular networks," in *Proc. of the 4th International Conference on Communications and Electronics (ICCE 2012)*, Hue, Vietnam, Aug. 2012.

[9] P. Asmus, A. Bae, B. Lockhart, N. Strother, and B. Gohn, "Smart grid: Ten trends to watch in 2012 and beyond," tech. rep., Pike Research LLC, 2012.

[10] National Energy Technology Laboratory, "Understanding the benefits of smart grid," tech. rep., 2010.

[11] F. Richter, A. Fehske, and G. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in *Proc. of the 70th IEEE Vehicular Technology Conference Fall (VTC 2009-Fall)*, Anchorage, Alaska, USA, Sep. 2009.

[12] 3rd Generation Partnership Project (3GPP), "3GPP TS 36.211 3GPP TSG RAN Evolved Universal Terrestrial Radio Access (E-UTRA) Physical Channels and Modulation, version 11.0.0, Release 11," 2012.

[13] K. Senthil and K. Manikandan, "Improved tabu search algorithm to economic emission dispatch with transmission line constraint," *International Journal of Computer Science and Communication*, vol. 1, no. 2, pp. 145–149, Jul-Dec. 2010.

[14] F. O. Hocaoglu, "Novel analytical hourly solar radiation models for photovoltaic based system sizing algorithms," in *Energy Conversion and Management, Vol. 51, No. 12, pp. 2921-2929*, Dec. 2010.

[15] J. Kim, V. S. Anil Kumar, A. Marathe, G. Pei, S. Saha, and B. S. P. Subbiah, "Modeling cellular network traffic with mobile call graph constraints," in *Proc. of the 2011 Winter Simulation Conference (WSC 2011)*, Phoenix, AZ, USA , Dec. 2011.

[16] M. A. Marsan and M. Meo, "Energy efficient management of two cellular access networks," in *Proc. of GreenMetrics Workshop in Conjunction with ACM SIGMETRICS Conference*, pp. 1–5, Washington, USA, Jun. 2009.

[17] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.