RESCUE: Renewable Energy Small Cells for Utility Enhancement in Green LTE HetNets

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***Abstract*—In this paper, the green operation of heterogeneous LTE cellular networks is investigated. In addition to macrocells, small cells are used to offload traffic and increase the capacity of the network. A combination of mains powered small cells and renewable energy small cells (RESC) is considered, where the latter correspond to small cell base stations (BSs) powered by renewable energy sources, e.g., solar panels or wind turbines. Thus, the presence of RESCs allows not only to offload macrocell traffic, but also to optimize energy performance by switching off other mains powered small cells whenever possible. Both the uplink (UL) and downlink (DL) directions are considered in the analysis, while taking into account dynamic resource allocation and the impact of intercell interference. A utility maximization approach is proposed, where weighted utility functions take into account both the quality of service (QoS) performance of the network and its energy consumption. The use of RESCs for utility enhancement (RESCUE) leads to interesting results, especially when the utility function presents a judicious balance between QoS and energy efficiency.**

***Index Terms*—LTE, heterogeneous networks, energy efficiency, green communications, utility maximization, renewable energy.**

I. Introduction

The explosion in rich media content, such as audio, video and gaming, is significantly increasing the load on cellular systems. State-of-the-art and next generation cellular systems have to cope with the mobile data growth. The number of cells required to meet the capacity demands is expected to increase significantly. Solutions to meet the increasing demand include the deployment of heterogeneous networks (HetNets) involving macrocells and small cells (picocells, femtocells, etc.), distributed antenna systems (DAS), coordinated multi point (CoMP) communication, relay stations (RS), and the use of D2D communications [1], [2]. In fact, HetNets are expected to constitute a paradigm shift in state-of-the-art cellular networks [3], and they constitute an interesting solution for network densification, which is a main theme for the evolution of cellular networks into 5G [2].

On the other hand, energy efficiency is representing an increasing concern for cellular network operators [4], [5]. Naturally, the main motivation is to minimize their electricity costs and maintain profitability. Nevertheless, reducing CO_2 emissions and other negative impacts on the environment are also important objectives [6]. In fact, a large portion of the energy dissipated in a cellular system is actually consumed at the base stations (BSs). Hence, putting certain BSs in sleep mode, or switching them off in light traffic conditions, is an efficient technique to save energy in wireless networks, e.g., see [7], [8]. In [9], BS switch-off techniques dependent on traffic conditions (time of day, day of week) are considered. However, the focus is on a single BS type, whereas HetNets and RESCs are left for future research. In [10], the cell size is adjusted dynamically depending on the traffic load using a technique called "cell zooming" for the purpose of reducing energy consumption. The power ratio, corresponding to the ratio between the dynamic and the fixed power part of a BS power consumption model, is introduced in [11]. This ratio is used to propose a solution based on traffic load balancing. In [12], an efficient, distributed, low complexity, and dynamic strategy is presented for switching cellular BSs on and off in order to achieve energy efficiency in green cellular networks. In most of these previous works, the focus is on downlink communication, and only macrocell BSs are considered.

Indeed, operating a dense HetNet in an energy-efficient manner with minimized energy consumption is a challenging task. In [13], energy efficiency in dense wireless local area network (WLAN) small cells is studied. Certain access points are put into sleep mode during periods of low user traffic in order to optimize the network energy consumption. In [14], cellular HetNets with small cells deployed at edges of macrocells are shown to lead to enhanced performance and reduced energy consumption, compared to macrocell networks and to HetNets with uniform small cell deployment. In [15], small cells with multi radio access technology (multi-RAT) support are considered. They can offload traffic from LTE to WiFi in order optimize coverage and boost the capacity of the cellular system. However, energy efficiency through on/off switching of small cells and macrocells in the uniform deployment, or the use of renewable energy sources, are not considered. In [16], a method based on Q-learning, named QC-learning, is proposed. It is used to offload traffic from macrocells to small cells. In addition, a distributed version is presented where a macro BS manages the small cell BSs in its area. Nevertheless, renewable energy is not considered as a source of power for small cells, neither radio resource management is taken into account to optimize QoS over the various subcarriers in an orthogonal frequency division multiple access (OFDMA) based system such as LTE/LTE-Advanced (LTE-A). A preliminary investigation of this scenario was performed by the author in [17], where it was shown that green HetNets outperform macrocells in terms of energy efficiency while meeting QoS requirements.

In this paper, extending the work in [17], the energy efficient operation of LTE-A networks in the HetNet scenario is investigated. In such a scenario, small cells can help offload traffic from macrocell BSs (the most energy consuming). Furthermore, green operation of the small cells themselves is studied, where for example a small cell can offload traffic from another small cell to put its neighbor BS in sleep mode (similarly to the techniques followed for macrocells). A combination of mains powered small cells and renewable energy small cells (RESC) is considered, where the latter correspond to small cell BSs powered by renewable energy sources such as solar panels or wind turbines. Consequently, RESCs allow not only the offload of macrocell traffic, but also the optimization of energy performance by switching off other mains powered small cells whenever possible, in order to reduce the mobile operator's electricity bill. Another contribution of this paper is the joint analysis of both the uplink (UL) and downlink (DL) performance, while taking into account dynamic resource allocation and the impact of intercell interference. A utility maximization approach is proposed, where weighted utility functions take into account both the quality of service (QoS) performance of the network and its energy consumption. Depending on the weights selected, different energy/performance tradeoffs can be achieved. The use of RESCs for utility enhancement (RESCUE), in conjunction with a utility maximization algorithm for BS on/off switching, leads to interesting results, especially when the utility function presents a judicious balance between QoS and energy efficiency.

The paper is organized as follows. The system model is described in Section II. The problem formulation and utility maximizing algorithm are presented in Section III. The utility metrics used in this paper are described in Section IV. Simulation results are presented and analyzed in Section V. Finally, the conclusions are presented in Section VI.

II. System Model

This section presents the system model. A general example is shown in Fig. 1, where Figs. 1 (a) and (b) show a macrocell and a HetNet deployment, respectively. In Fig. 1 (b), the joint operation different types of small cells and advanced techniques lead to enhancing energy efficiency by putting the upper left BS of Fig. 1 (b) in sleep mode: microcells (b1), indoor outdoor offloading through femtocells/Home Node Bs/WiFi access points (b2), relays (b3), DAS (b4), and CoMP(b5).

In this paper, a geographical area of interest with a uniform user distribution is considered. The area is covered by an LTE network. It is subdivided into cells of equal size, with a BS placed at the center of each cell. Macrocell BSs are deployed to cover a cell radius R_M. A network of small cell BSs is overlaid on top of the macrocell network, with each small cell BS covering a smaller cell radius $R_S < R_M$. A fraction η of the small cell BSs are RESCs powered by renewable energy sources, such as solar panels, whereas $1 - \eta$ of the small cell BSs, along with all the macro BSs, are powered through the mains power grid. The method presented in Sections III and IV will be used to switch-off certain BSs according to a certain network utility metric.

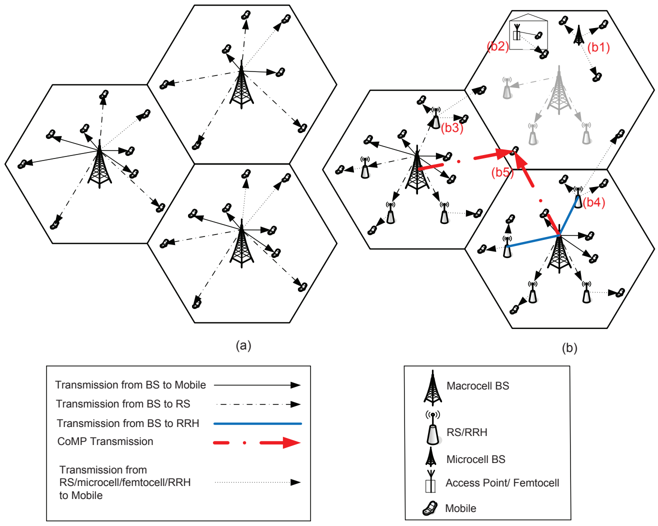

Fig. 1. Network Example: (a) Macrocell only. (b): Green heterogeneous network.

This leads to energy savings and contributes in achieving green communications in the deployed LTE network. The economic savings from using RESCs were studied in [18], and dimensioning the solar panels and wind turbines to secure the needed energy was analyzed in [19]. It was shown that smart policies (e.g., switch on-off) have to be considered to avoid unrealistic photovoltaic panel dimensions. In practice, whenever possible, small cells would ideally have access to both mains power and renewable energy sources. Whenever the small cell BS has to be switched on to maintain QoS, it will use the energy from the traditional electric grid to complement the insufficiency of its available renewable energy at that time. This process is abstracted in this paper by assuming that, at any given time, a portion η of small cell BSs are powered by renewable energy sources, whereas the rest are using the mains power grid. This portion η is varied randomly at each simulation run, to model the effect of consuming the renewable energy in different BSs at different times depending on the load and the on/off switching approach.

In LTE/LTE-A, OFDMA is the access scheme for the DL, whereas single carrier frequency division multiple access (SCFDMA), a modified form of OFDMA, is used in the UL in order to reduce the high peak to average power ratio (PAPR) inherent in OFDMA systems [20]. According to the standard, the available LTE spectrum is divided into resource blocks (RB) consisting of 12 adjacent subcarriers. The assignment of a single RB takes place every 1 ms, or equivalently, over two 0.5 ms time slots forming a single transmission time interval (TTI) [21]. The LTE standard imposes the constraint that the RBs allocated to a single user should be consecutive with equal power allocation over the RBs [20], [21], [22].

A. Channel Model

We consider a channel model consisting of pathloss, log-normal shadowing, and fast Rayleigh fading as described in [23], [24]. Hence, the channel gain over subcarrier i between user k_l in cell l and BS j is given by:

$$H_{k_l,i,j,\text{dB}} = (-\kappa - \upsilon \log_{10} d_{k_l,j}) - \xi_{k_l,i,j} + 10\log_{10} F_{k_l,i,j} \tag{1}$$

where propagation loss is captured in the first factor: κ is the pathloss constant, υ the path loss exponent, and $d_{k_l,j}$ is the distance in km from user k_l to BS j. Log-normal shadowing, $\xi_{k_l,i,j}$,, is represented by the second factor in 1, where a zero-mean and a standard deviation σ_ξ are considered. Rayleigh fading is taken into account in the last factor, $F_{k_l,i,j}$, where a Rayleigh parameter a, usually selected such that $E[a^2] = 1$ (with $E[\cdot]$ the expectation operator), is assumed.

The notation $H^{(\text{UL})}_{k_l,i,j}$ and $H^{(\text{DL})}_{k_l,i,j}$ will be used in the sequel, in order to differentiate between UL and DL subcarriers, respectively.

B. Data Rates in the Downlink

We denote by $\mathcal{I}^{(\text{DL})}_{\text{sub},k_l}$ and $\mathcal{I}^{(\text{DL})}_{\text{RB},k_l}$ the sets of subcarriers and RBs, respectively, allocated for DL transmission to user k_l in cell l. Let $N^{(\text{DL})}_{\text{RB}}$ be the total number of RBs in the DL, L the number of BSs, K_l the number of users in cell l, $P^{(\text{DL})}_{i,l}$ the power transmitted by the BS over subcarrier i in cell l, $P^{(\text{DL})}_{l,\max}$ the maximum transmission power of BS l, and $R^{(\text{DL})}_{k_l}$ the achievable DL rate of user k_l in cell l, then the OFDMA throughput of user k_l in cell l is given by:

$$R^{(\text{DL})}_{k_l}(\mathbf{P}^{(\text{DL})}_{\mathbf{l}}, \mathcal{I}^{(\text{DL})}_{\text{sub},k_l}) = \sum_{i\in\mathcal{I}^{(\text{DL})}_{\text{sub},k_l}} B^{(\text{DL})}_{\text{sub}} \cdot \log_2\left(1 + \gamma^{(\text{DL})}_{k_l,i,l}\right) \tag{2}$$

where $B^{(\text{DL})}_{\text{sub}}$ is the subcarrier bandwidth. It is expressed as:

$$B^{(\text{DL})}_{\text{sub}} = \frac{B^{(\text{DL})}}{N^{(\text{DL})}_{\text{sub}}} \tag{3}$$

with $B^{(\text{DL})}$ the total usable DL bandwidth, and $N^{(\text{DL})}_{\text{sub}}$ the total number of DL subcarriers.

In addition, in (2), $\mathbf{P}^{(\text{DL})}_{\mathbf{l}}$ represents a vector of the transmitted power on each subcarrier by BS l, $P^{(\text{DL})}_{i,l}$. In this paper, the transmit power is considered to be equally allocated over the subcarriers. Hence, for all i:

$$P^{(\text{DL})}_{i,l} = \frac{P^{(\text{DL})}_{l,\max}}{N^{(\text{DL})}_{\text{sub}}} \tag{4}$$

The signal to interference plus noise ratio (SINR) of user k_l over subcarrier i in cell l in the DL, $\gamma^{(\text{DL})}_{k_l,i,l}$, is expressed as:

$$\gamma^{(\text{DL})}_{k_l,i,l} = \frac{P^{(\text{DL})}_{i,l} H^{(\text{DL})}_{k_l,i,l}}{I^{(\text{DL})}_{i,k_l} + \sigma^2_{i,k_l}} \tag{5}$$

where σ^2_{i,k_l} is the noise power over subcarrier i in the receiver of user k_l, and $I^{(\text{DL})}_{i,k_l}$ is the interference on subcarrier i measured at the receiver of user k_l. The expression of the interference is given by:

$$I_{i,k_l} = \sum_{j\neq l, j=1}^{L} \left(\sum_{k_j=1}^{K_j} \alpha^{(\text{DL})}_{k_j,i,j} \right) \cdot P^{(\text{DL})}_{i,j} H^{(\text{DL})}_{k_l,i,j} \tag{6}$$

In (6), $\alpha^{(\text{DL})}_{k_j,i,j}$ is a binary variable representing the exclusivity of subcarrier allocation: $\alpha^{(\text{DL})}_{k_j,i,j} = 1$ if DL subcarrier i is allocated to user k_j in cell j, i.e., $i \in \mathcal{I}^{(\text{DL})}_{\text{sub},k_j}$, and $\alpha_{k_j,i,j} = 0$ otherwise. In fact, in each cell, an LTE RB, along with the subcarriers constituting that RB, can be allocated to a single user at a given TTI. Consequently, the following is verified in each cell j:

$$\sum_{k_j=1}^{K_j} \alpha^{(\text{DL})}_{k_j,i,j} \leq 1 \tag{7}$$

C. Data Rates in the Uplink

We denote by $\mathcal{I}^{(\text{UL})}_{\text{sub},k_l}$ and $\mathcal{I}^{(\text{UL})}_{\text{RB},k_l}$ the sets of UL subcarriers and RBs, respectively, allocated to user k_l in cell l. Let $N^{(\text{UL})}_{\text{sub}}$ and $N^{(\text{UL})}_{(\text{RB})}$ be the total number of subcarriers and RBs, respectively, in the UL, $P^{(\text{UL})}_{k_l,i,l}$ the power transmitted by user k_l over subcarrier i in cell l, $P^{(\text{UL})}_{k_l,\max}$ the maximum transmission power of user k_l, and $R^{(\text{UL})}_{k_l}$ its achievable rate in the UL. The SCFDMA throughput of user k_l in cell l can then be expressed as:

$$R^{(\text{UL})}_{k_l}(\mathbf{P}^{(\text{UL})}_{\mathbf{k_l}}, \mathcal{I}^{(\text{UL})}_{\text{sub},k_l}) = \frac{B^{(\text{UL})}|\mathcal{I}^{(\text{UL})}_{\text{sub},k_l}|}{N^{(\text{UL})}_{\text{sub}}} \cdot \log_2\left(1 + \gamma^{(\text{UL})}_{k_l}(\mathbf{P}^{(\text{UL})}_{\mathbf{k_l}}, \mathcal{I}^{(\text{UL})}_{\text{sub},k_l})\right) \tag{8}$$

where $|\cdot|$ represents set cardinality, $B^{(\text{UL})}$ is the total UL bandwidth, and $\mathbf{P}^{(\text{UL})}_{\mathbf{k_l}}$ represents a vector of the transmitted power on each subcarrier, $P_{k_l,i,l}$. Finally, the term $\gamma^{(\text{UL})}_{k_l}(\mathbf{P}^{(\text{UL})}_{\mathbf{k_l}}, \mathcal{I}^{(\text{UL})}_{\text{sub},k_l})$ represents the UL SINR of user k_l after minimum mean squared error (MMSE) frequency domain equalization at the receiver [25]:

$$\gamma^{(\text{UL})}_{k_l}(\mathbf{P}^{(\text{UL})}_{\mathbf{k_l}}, \mathcal{I}^{(\text{UL})}_{\text{sub},k_l}) = \left(\frac{1}{\frac{1}{|\mathcal{I}^{(\text{UL})}_{\text{sub},k_l}|} \sum_{i\epsilon\mathcal{I}^{(\text{UL})}_{\text{sub},k_l}} \frac{\gamma^{(\text{UL})}_{k_l,i,l}}{\gamma^{(\text{UL})}_{k_l,i,l} + 1}} - 1 \right)^{-1} \tag{9}$$

In (9), $\gamma^{(\text{UL})}_{k_l,i,l}$ is the UL SINR of user k_l over subcarrier i in cell l, expressed as:

$$\gamma^{(\text{UL})}_{k_l,i,l} = \frac{P^{(\text{UL})}_{k_l,i,l} H^{(\text{UL})}_{k_l,i,l}}{I^{(\text{UL})}_{i,l} + \sigma^2_{i,l}} \tag{10}$$

where $\sigma^2_{i,l}$ is the noise power over subcarrier i in cell l, and $I^{(\text{UL})}_{i,l}$ is the UL interference on subcarrier i measured at BS l. The interference expression is given by:

$$I^{(\text{UL})}_{i,l} = \sum_{j\neq l, j=1}^{L} \sum_{k_j=1}^{K_j} \alpha^{(\text{UL})}_{k_j,i,j} P^{(\text{UL})}_{k_j,i,j} H^{(\text{UL})}_{k_j,i,l} \tag{11}$$

where $\alpha^{(\text{UL})}_{k_l,i,l} = 1$ if subcarrier i is allocated to user k_l in cell l, i.e., $i \in \mathcal{I}^{(\text{UL})}_{\text{sub},k_l}$. Otherwise, $\alpha^{(\text{UL})}_{k_l,i,l} = 0$.

The LTE standard imposes the constraint that the UL RBs that are allocated to a single user should be consecutive with equal power allocation over the RBs [20], [21], [22]. Consequently, the UL transmit power of user k_l over subcarrier i in cell l is given by:

$$P_{k_l,i,l}^{(\mathrm{UL})} = \frac{P_{k_l,\max}^{(\mathrm{UL})}}{|\mathcal{I}_{\mathrm{sub},k_l}^{(\mathrm{UL})}|} \tag{12}$$

D. Admission Control and Resource Allocation

When a user k joins the network, it is associated with cell l^* and the UL RB for which the subcarriers $i^{*(\mathrm{UL})}$ satisfy:

$$(i^{*(\mathrm{UL})}, l^*) = \arg\max_{(i,l)} \left(1 - \sum_{k_l=1;k_l\neq k}^{K_l} \alpha_{k_l,i,l}^{(\mathrm{UL})}\right) H_{k,i,l}^{(\mathrm{UL})} \tag{13}$$

It is then allocated the DL RB in cell l^* for which the subcarriers $i^{*(\mathrm{DL})}$ satisfy:

$$i^{*(\mathrm{DL})} = \arg\max_{i} \left(1 - \sum_{k_l=1;k_l\neq k}^{K_l} \alpha_{k_l,i,l^*}^{(\mathrm{DL})}\right) H_{k,i,l^*}^{(\mathrm{DL})} \tag{14}$$

In (13) and (14), the first term in the multiplication indicates that the search is on the RBs that are not yet allocated to other users. It should be noted that the subcarriers constituting a single RB are considered to be subjected to the same fading and hence the channel gain on the subcarriers of a single RB is approximately the same. Furthermore, the fading is assumed to be independent identically distributed (iid) across RBs. In this paper, resource allocation is performed as described above, where one UL RB and one DL RB are allocated for each user. However, the proposed method described in Sections III and IV is applicable with any resource allocation algorithm.

After completing user-BS association and performing resource allocation, the rates (2) and (8) are calculated. To represent the QoS constraints of a given user k_l in cell l, two target rates in the UL and DL, $R_{\mathrm{Target},k_l}^{(\mathrm{UL})}$ and $R_{\mathrm{Target},k_l}^{(\mathrm{DL})}$, respectively, are considered. A user is successfully served and satisfies its QoS requirements if the following conditions are met:

$$\begin{cases} R_{k_l}^{(\mathrm{UL})} \geq R_{\mathrm{Target},k_l}^{(\mathrm{UL})} \\ R_{k_l}^{(\mathrm{DL})} \geq R_{\mathrm{Target},k_l}^{(\mathrm{DL})} \end{cases} \tag{15}$$

If any of the conditions in (15) is not satisfied, the user is considered to be in outage.

E. BS Power Consumption

In general, BS power consumption comprises a fixed term due to the energy consumed as part of the normal power operation of the BS (e.g. internal processing, air conditioning, etc. [26]), and a variable term that depends on the transmission load [27], [28]. For small cells, the power consumed can be approximated as a load independent term [27], [28], unlike macrocells. However, even in macrocells, most of the power consumption is absorbed by the load independent term. Therefore, in this paper, a worst case scenario is considered where the BSs are considered to operate at full power. In fact, the system model considered is dominated by a vast majority of small cells, and a small fraction of macrocells. **The term $P_{\mathrm{C},l}$ is used to denote the total power consumed by BS l (not to be confused with the transmit power at the antenna, which is included as a fraction of this power term). The values for this parameter are set to $P_{\mathrm{C},l} = 500$ W for macrocell BSs, $P_{\mathrm{C},l} = 100$ W for mains powered small cell BSs, and to $P_{\mathrm{C},l} = 0$ W for RESCs. These numbers are within the ranges presented in [29].** In addition, for macrocells, the maximum transmit power in the simulations of Section V is set to $P_{l,\max}^{(\mathrm{DL})} = 10$ W, which corresponds to only 2% of the total BS power consumption for macrocell BSs (It is set to $P_{l,\max}^{(\mathrm{DL})} = 1$ W for small cell BSs). Hence, this also justifies the use of the worst case full power scenario for active BSs in this paper.

III. PROPOSED APPROACH

In this section, the details of the proposed green communications method are presented. After users join the network and are associated with their respective BSs (macrocell or small cell BSs), the utility of each cell can then be calculated. The utility is used as a performance metric to determine if a certain cell should be switched off or kept on. After calculating the utilities, the proposed green communications algorithm is implemented.

A. Problem Formulation

Considering there are N_{BS} BSs in the network, each having its own utility, with U_l denoting the utility of BS l, then the objective is to maximize the total network utility as follows:

$$\max_{\alpha_{k_l,i,l}^{(\mathrm{DL})}, \alpha_{k_l,i,l}^{(\mathrm{UL})}, P_l^{(\mathrm{DL})}, P_{k_l}^{(\mathrm{UL})}, I_l^{\mathrm{ON}}} \left(\sum_{l=1}^{N_{\mathrm{BS}}} U_l\right) \tag{16}$$

Subject to:

$$0 \leq P_{k_l}^{(\mathrm{UL})} \leq P_{k_l,\max}^{(\mathrm{UL})}; \forall k_l = 1, ..., K_l; \forall l = 1, ..., N_{\mathrm{BS}} \tag{17}$$

$$0 \leq P_l^{(\mathrm{DL})} \leq P_{l,\max}^{(\mathrm{DL})}; \forall l = 1, ..., N_{\mathrm{BS}} \tag{18}$$

$$\sum_{k_l=1}^{K_l} \alpha_{k_l,i,l}^{(\mathrm{UL})} \leq 1; \forall i = 1, ..., N_{\mathrm{sub}}^{(\mathrm{UL})}; \forall l = 1, ..., N_{\mathrm{BS}} \tag{19}$$

$$\sum_{k_l=1}^{K_l} \alpha_{k_l,i,l}^{(\mathrm{DL})} \leq 1; \forall i = 1, ..., N_{\mathrm{sub}}^{(\mathrm{DL})}; \forall l = 1, ..., N_{\mathrm{BS}} \tag{20}$$

$$\sum_{l=1}^{N_{\mathrm{BS}}} \frac{N_{\mathrm{out},l}}{N_{\mathrm{served},l} + N_{\mathrm{out},l}} \leq P_{\mathrm{out,th}} \tag{21}$$

$$\alpha_{k_l,i,l}^{(\mathrm{DL})}, \alpha_{k_l,i,l}^{(\mathrm{UL})}, I_l^{\mathrm{ON}} \in \{0, 1\}; \forall i, k, l \tag{22}$$

The constraints in (17) and (18) indicate that the transmit power cannot exceed the maximum power for the UL and DL, respectively. The constraints in (19) and (20) correspond to the exclusivity of subcarrier allocations in each cell for the

UL and DL, respectively, since in each cell, a subcarrier can be allocated at most to a single user at a given TTI. The constraint in (21) is related to enforcing QoS, where $N_{\text{out},l}$ corresponds to the number of users in outage in cell l, i.e., the users associated with cell l as their best serving cell according to (13) and (14), but that were not able to satisfy their QoS requirements in (15). $N_{\text{served},l}$ indicates the number of users served successfully in cell l. Hence, this constraint indicates that the total outage rate in the network should not exceed a tolerated outage threshold $P_{\text{out,th}}$. The variable I_j^{ON} is an indicator variable defining if a BS j is on or off, by setting its value to 1 or 0, respectively. The last constraint in (22) is a trivial one to indicate the type of the binary variables.

The utility function would depend on the network QoS, and consequently on the achievable data rates, which depend on the user SINRs. Hence, from (5), (6), (10), and (11), selecting "optimal" values for $\left\{\alpha_{k_l,i,l}^{(\text{DL})}, \alpha_{k_l,i,l}^{(\text{UL})}, P_l^{(\text{DL})}, P_{k_l}^{(\text{UL})}, I_l^{\text{ON}}\right\}$ at a given cell l will change the interference values at the other cells, which would necessitate optimizing again the values of these parameters at these cells. This in turn will impact the interference values and SINR expressions again at cell l. This intertwining between the optimization parameters makes the problem a mixed-integer non linear program. Due to the difficulty of solving such a problem, a low complexity algorithm is presented next.

B. Low Complexity Green Heuristic Algorithm

To perform this sum-utility maximization, Algorithm 1 is implemented. In this algorithm, we introduce another indicator variable in addition to I_j^{ON}: I_j^{attempt} is a tracking parameter that indicates whether an attempt has been made to switch BS j off in the current iteration or not. It is set to 1 if the attempt was made and to 0 otherwise. The loop at Lines 1-4 is an initialization phase. In the Loop at Lines 5-23, the algorithm finds the BS having the weakest individual utility, then checks if the reassignment of its users to other BSs and putting it in sleep mode leads to an enhancement for the network utility. If an enhancement is reached, the BS is switched off. Otherwise it is kept on. Then the algorithm moves to the next BS, and so on. The iterations are repeated until no improvement can be made in the sum-utility, even if an attempt is made on all the BSs that remained "on" (which in this case will lead to $\prod_{j=1;I_j^{\text{ON}}=1}^{N_{\text{BS}}} I_j^{\text{attempt}} = 1$ and allows to exit the loop at Line 5).

Although Algorithm 1 assumes central control over all BSs, it still can be implemented locally in a distributed way. In fact, a user cannot "hear" the pilot signals of all BSs and thus it can send measurement reports about a limited number of BSs in the network, generally the ones in its surroundings. These BSs can share the needed information over the X2 interface in LTE, and the on/off switching decisions can be made locally, similarly to the approach described in [12].

C. Complexity Analysis

Lines 1-3 of Algorithm 1 consist of an initialization step. The complexity of the step at Line 6 is of the order of N_{BS}.

Algorithm 1 Utility Maximization Algorithm

1: **for all** BS j **do**
2: $\quad I_j^{\text{ON}} = 1$
3: $\quad I_j^{\text{attempt}} = 0$
4: **end for**
5: **while** $\prod_{j=1;I_j^{\text{ON}}=1}^{N_{\text{BS}}} I_j^{\text{attempt}} = 0$ **do**
6: $\quad$ Find: $j^* = \arg \min_{I_j^{\text{ON}}=1, I_j^{\text{attempt}}=0} U_j$
7: $\quad$ **for all** k_{j^*} served by BS j^* **do**
8: $\quad\quad$ Implement (13) and (14) after excluding j^* from the BS search in (13); i.e the search is done over BSs $l \neq j^*$
9: $\quad$ **end for**
10: $\quad$ **for all** $j \neq j^*$ such that $I_j^{\text{ON}} = 1$ **do**
11: $\quad\quad$ Compute $U_j^{(\text{new})}$ obtained after moving the users k_{j^*} as described above
12: $\quad\quad$ Set $U_{j^*}^{(\text{new})} = 0$
13: $\quad$ **end for**
14: $\quad$ **if** $\sum_{j=1}^{N_{\text{BS}}} U_j^{(\text{new})} > \sum_{j=1}^{N_{\text{BS}}} U_j$ **and** (21) is verified **then**
15: $\quad\quad$ **for all** j such that $I_j^{\text{ON}} = 1$ **do**
16: $\quad\quad\quad$ Set: $U_j = U_j^{(\text{new})}$ and $I_j^{\text{attempt}} = 0$
17: $\quad\quad\quad$ Set: $I_{j^*}^{\text{ON}} = 0$
18: $\quad\quad$ **end for**
19: $\quad$ **else**
20: $\quad\quad$ No changes are made (Keep the old utility values)
21: $\quad\quad$ Set: $I_{j^*}^{\text{attempt}} = 1$
22: $\quad$ **end if**
23: **end while**

In the loop at Lines 7-9, the search for each user is over active BSs and their RBs, thus it involves at most $N_{\text{RB}}(N_{\text{BS}} - 1)$ combinations of (RB, BS). As the process is repeated for all users K_l in a given cell l, the worst case complexity of this loop becomes $\mathcal{O}(\max_l K_l N_{\text{RB}}(N_{\text{BS}} - 1))$. Since the main loop of the algorithm at lines 5-23 iterates over all BSs, the worst case complexity of the iterative loop becomes $\mathcal{O}(N_{\text{RB}} K N_{\text{BS}}(N_{\text{BS}} - 1)) \simeq \mathcal{O}(N_{\text{RB}} K N_{\text{BS}}^2)$, where $K = \sum_l K_l$ represents all users in the network and is used to correspond to the worst-case complexity.

Denoting by J the number of iterations needed to have $\prod_{j=1;I_j^{\text{ON}}=1}^{N_{\text{BS}}} I_j^{\text{attempt}} = 1$ in order to break the loop at Line 5, the complexity of the algorithm becomes $\mathcal{O}(J N_{\text{RB}} K N_{\text{BS}}^2)$. It should be noted that this is a worst-case complexity. The actual complexity is less due to switching BSs off as the algorithm progresses (and hence excluding them from the search) and due to the fact that a user does not "hear" the pilot signals of all BSs. Consequently, only the BSs with which it has a relatively good link quality will be included in the search. In fact, the algorithm can be implemented locally at certain BS clusters involving a limited number of BSs.

IV. Utility Calculations

This section presents the utility metrics used with the green approach of Section III. Utility maximization has long been an active research topic for radio resource management, HetNets, and multi-RAT networks, e.g., [15], [30], [31]. In this section, novel utility metrics are proposed in order to take into account energy efficiency in green HetNets and user QoS simultaneously. Different utility metrics are derived depending on the weight given to each of these parameters. The results of Section V demonstrate the performance of each of the proposed utility metrics.

A weighted utility is considered as follows:

$$U_l = \omega U_{1,l} + (1-\omega) U_{2,l} \tag{23}$$

where ω is a weight parameter such that $0 \leq \omega \leq 1$. The term $U_{1,l}$ corresponds to the QoS performance and user satisfaction in the coverage area of BS l, whereas $U_{2,l}$ captures the power consumption at BS l. Different functions can be used for these utilities. The ones selected in this paper along with their justification are presented next.

The term $U_{1,l}$ is selected as follows:

$$U_{1,l} = N_{\text{served},l} \cdot \exp\left(P_{\text{out,th}} - \frac{N_{\text{out},l}}{N_{\text{served},l} + N_{\text{out},l}}\right) \tag{24}$$

It clearly depends on the traffic load and QoS performance of each BS. In fact, the utility in (24) increases with the number of served users and decreases with the number of users in outage. When the tolerated threshold $P_{\text{out,th}}$ is exceeded, the exponential term in (23) becomes negative and the utility starts decreasing quickly towards zero. If no users are served by a certain BS, then $U_{1,l} = 0$, which favors switching off BS l by Algorithm 1.

The second term $U_{2,l}$ is selected as follows:

$$U_{2,l} = -\frac{P_{\text{C},l}}{N_{\text{served},l}} \tag{25}$$

where $P_{\text{C},l}$ is the total power consumed by BS l (not to be confused with the transmit power at the antenna, which is included as a fraction of this power term). In general, utilities aiming at maximizing the sum rate while being concerned with energy efficiency can be defined in terms of bps/Hz/Watt. However, in this paper, the interest is in maximizing the number of served users satisfying the constraints in (15), while minimizing the power consumption in the network. Thus, when $\omega = 0$, maximizing (23) becomes a maximization of the number of served users versus the power consumption in the network. In fact,

$$\max\left(-\frac{P_{\text{C},l}}{N_{\text{served},l}}\right) \Leftrightarrow \max \frac{N_{\text{served},l}}{P_{\text{C},l}} \tag{26}$$

Clearly, maximizing (24) and (25) corresponds to $\omega = 1$ and $\omega = 0$, respectively. A situation that ensures a balanced tradeoff between these two extreme scenarios could correspond to $\omega = 0.5$, or equivalently:

$$U_l = N_{\text{served},l} \cdot \exp\left(P_{\text{out,th}} - \frac{N_{\text{out},l}}{N_{\text{served},l} + N_{\text{out},l}}\right) - \frac{P_{\text{C},l}}{N_{\text{served},l}} \tag{27}$$

Indeed, the expression in (27) increases with the number of served users, and decreases with the number of users in outage and with the network power consumption. It could lead to interesting results by offloading users to be served by RESC BSs. The results of Section V will show a comparison of these utilities with $\omega = 0$, $\omega = 0.5$, and $\omega = 1$.

V. Results and Discussion

A uniform user distribution is considered over a coverage area of size 5×5 km^2. BSs are placed on a rectangular grid uniformly in the area. The cell radii are set to $R_M = 0.5$ km and $R_S = 0.1$ km for macrocells and small cells, respectively. The transmit power is set to $P_{l,\max}^{(\text{DL})} = 10$ W for macrocell BSs, $P_{l,\max}^{(\text{DL})} = 1$ W for small cell BSs, and $P_{k_l,\max}^{(\text{UL})} = 0.125$ W for mobile devices. The power consumption is set to $P_{\text{C},l} = 500$ W for macrocell BSs. It is set to $P_{\text{C},l} = 100$ W for mains powered small cell BSs, and to $P_{\text{C},l} = 0$ W for RESCs. The outage threshold is set to $P_{\text{out,th}} = 0.05$. An LTE bandwidth of 10 MHz is considered for each of the UL and DL directions, subdivided into 50 RBs. LTE parameters are obtained from [22], [32], and channel parameters are obtained from [24]. The network performance is analyzed under different services depending on their UL and DL target data rates. They are presented in Table I. Service 1 represents, for example, a symmetric voice service. Services 2 and 4 are asymmetric services with various UL/DL rate combinations (e.g., similar to fixed ADSL services). Scenario 3 is a symmetric service with rates sufficient for video conferencing. It should be noted that significantly higher data rates can be reached compared to these services when the whole LTE bandwidth of 20 MHz (100 RBs) is allocated to a single user in the absence of interference. However, the services of Table I are more realistic in the case of one RB allocated per user in a loaded network with high interference levels.

The simulation results are shown in Figs. 2 to 5 for Services 1-4, respectively. The comparison is performed between the traditional scenario (i.e. without implementing green networking techniques: all 25 macro BSs and 625 small cell BSs are always on) with $\eta = 0$ (all small cells mains powered) and $\eta = 0.5$ (50% of small cells are RESCs), the case $\omega = 1$ (Utility 1, with which the Algorithm is insensitive to the presence or absence of RESCs), $\omega = 0$ (Utility 2) with $\eta = 0$ and $\eta = 0.5$, and $\omega = 0.5$ (Utility 3) with $\eta = 0.5$.

It can be seen that the implementation of the green networking methods leads to significant energy gains compared to the traditional scenarios, for all the considered utilities. All the compared methods also lead to an outage rate below the target threshold. In addition, Utility 1 leads to the best QoS results (less outage) compared to the other methods, at the expense of higher energy consumption due to more active BSs. This is expected, since Utility 1 does not include a term that penalizes power consumption, and focuses only on the

TABLE I
Services Studied in the Simulations.

Service	$R_{\text{Target},k_l}^{(\text{UL})}$ (kbps)	$R_{\text{Target},k_l}^{(\text{DL})}$ (kbps)
Service 1	64	64
Service 2	56	256
Service 3	384	384
Service 4	384	1000

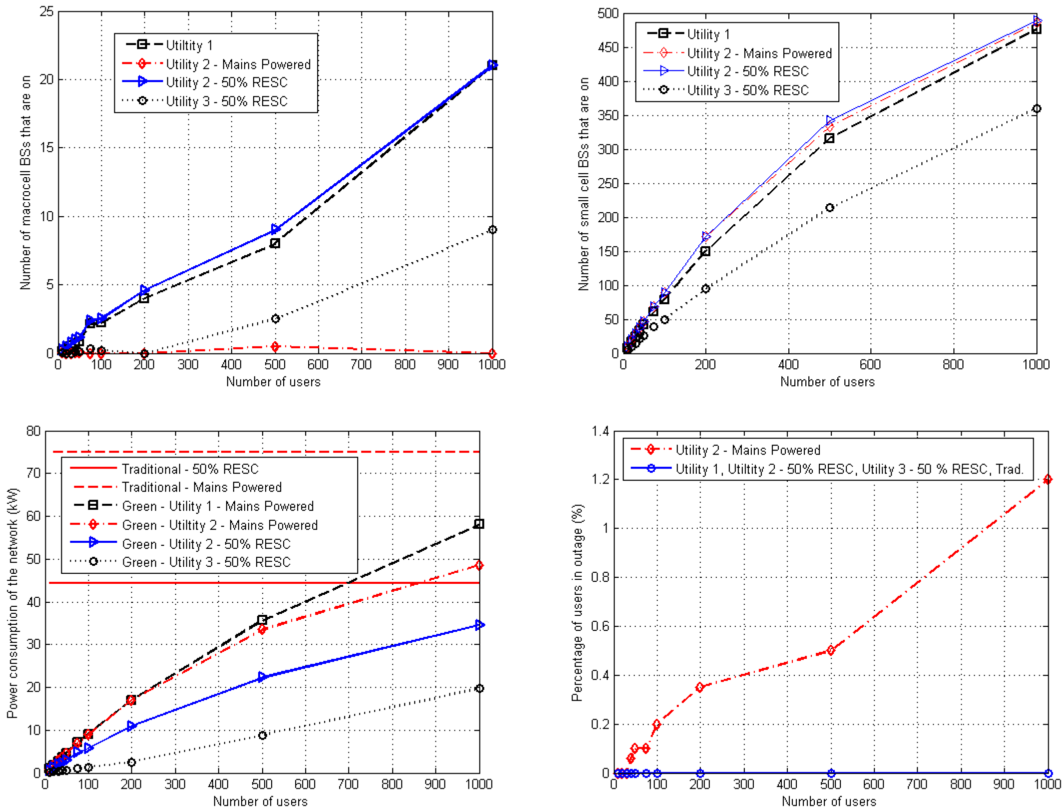

Fig. 2. Performance results for Service 1. Upper Left: Number of macrocell BSs switched on. Upper Right: Number of small cell BSs switched on. Bottom Left: Network power consumption. Bottom Right: Percentage of users in outage.

QoS performance of the network. On the other hand, Utility 2 has better energy efficiency than Utility 1, at the expense of worse QoS performance. In fact, although Utility 2 depends on the number of served users, its expression is independent from the number of users in outage. Another interesting result can be noted with Utility 2: With 100% mains powered small cells ($\eta = 0$), Utility 2 leads to the switch off of most of the macrocell BSs in order to save energy, whereas in the case of 50% RESCs, it has a higher number of active macrocell and small cell BSs with a lower network power consumption than Utility 1 and Utility 2 with $\eta = 0$. This is due to activating a larger number of RESCs and putting mains power small cell BSs into sleep mode, which permits the activation of additional macro BSs while still leading to lower power consumption.

The implementation of the green networking techniques has a desirable interference mitigation effect. In fact, due to minimizing the number of active BSs, overall interference in the network is reduced. This leads to higher SINRs and thus less users in outage compared to the traditional scenario. This is mostly true with outage aware utilities (Utilities 1 and 3). The power aware utility (Utility 2) with $\eta = 0.5$ leads to similar outage results compared to the traditional case. This is explained by the fact that this utility is more power oriented, and tries to reduce the transmit power without being too sensitive to outage results (although it depends on the number of served users). With $\eta = 0$, Utility 2 leads to higher outage than the traditional case for Services 1, 2, and 3. This is due to switching off additional BSs in order to reduce power consumption and enhance the utility, at the expense of degraded QoS, although without exceeding the outage constraint $P_{\mathrm{out,th}}$. In fact, it can be noticed that Utility 3 leads to lower power consumption than Utility 2, although Utility 2 is more power oriented, whereas Utility 3 represents a tradeoff between QoS and power consumption. This is explained by the fact that Utility 2 must keep a certain number of BSs active in order to satisfy the outage constraint. Otherwise, it tends to switch too many BSs off. Since this utility is not outage aware, the benefits of power saving are partially overrun by the need to respect the outage constraint. This is not the case with Utility 3, which is both power and outage aware. Hence, it allows more BSs to be put to sleep without risking to violate the outage constraint.

Figs. 2 to 5 show that the best tradeoffs are achieved with Utility 3 with $\eta = 0.5$. This utility leads to the lowest energy consumption in the network while having an outage rate close to, but slightly higher than the case of Utility 1. This is due to the fact that Utility 3 is a weighted sum of an outage sensitive term and a power sensitive term. This allows the green algorithm to converge to an energy efficient and performance efficient solution, particularly due to the presence of RESCs. This allows the green implementation with Utility 3 to judiciously activate a certain number of macro BSs to benefit from their higher transmit power, while using less small cells, and increasing the proportion of RESCs among the active small cell BSs.

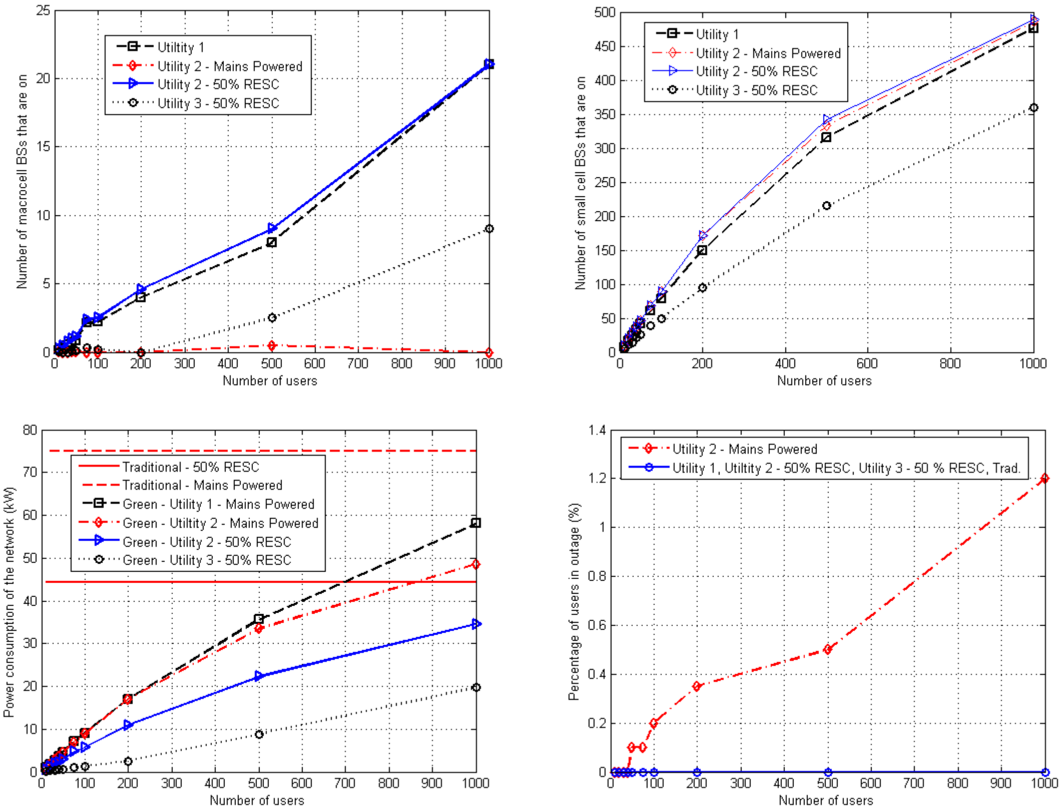

Fig. 3. Performance results for Service 2. Upper Left: Number of macrocell BSs switched on. Upper Right: Number of small cell BSs switched on. Bottom Left: Network power consumption. Bottom Right: Percentage of users in outage.

VI. Conclusions

The green operation of heterogeneous LTE cellular networks was investigated using small cell base stations powered by renewable energy sources along with other mains powered small cell base stations. The analysis englobed both the uplink and downlink directions, while taking into account dynamic resource allocation and the impact of intercell interference. The energy minimization problem was formulated as a utility maximization problem, and a low complexity heuristic utility maximization algorithm was proposed. Furthermore, weighted utility functions taking into account both quality of service and energy efficiency were proposed. Performance tradeoffs depending on the utility selected were studied, and significant energy savings were reached with the proposed approach, along with enhanced QoS in the network, especially when the selected utility function presented a balance between QoS and energy efficiency. This led to offloading traffic not only from macrocells to small cells, but also from mains powered small cells to renewable energy powered small cells.

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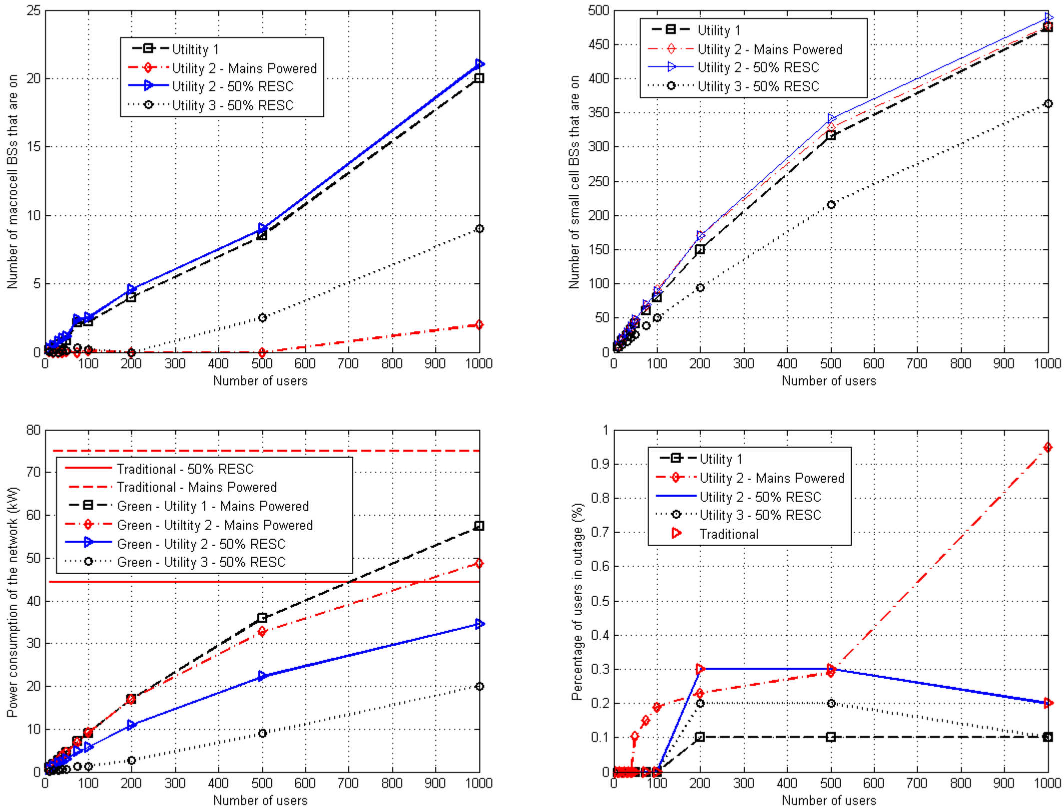

Fig. 4. Performance results for Service 3. Upper Left: Number of macrocell BSs switched on. Upper Right: Number of small cell BSs switched on. Bottom Left: Network power consumption. Bottom Right: Percentage of users in outage.

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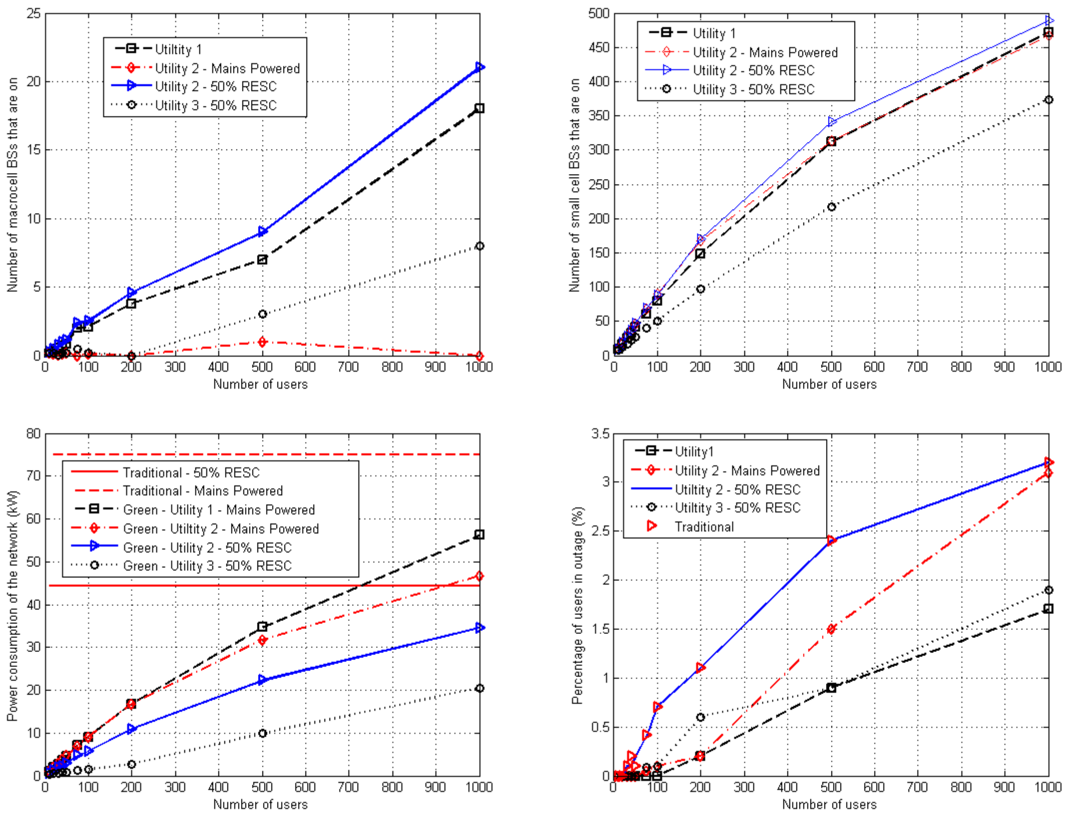

Fig. 5. Performance results for Service 4. Upper Left: Number of macrocell BSs switched on. Upper Right: Number of small cell BSs switched on. Bottom Left: Network power consumption. Bottom Right: Percentage of users in outage.