A Model to Analyze the Energy Savings of Base Station Sleep Mode in LTE HetNets

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***Abstract*—In this paper we study the base station (BS) sleep mode as an approach to decrease the energy consumption of LTE HetNets. We present an energy model which takes into account that (i) macro, micro and pico BSs have different power consumption profiles, (ii) macro BS power consumption is varying with the load, and (iii) communication through a macro, micro or pico cell has different radio resource utilization. Furthermore, we introduce two sleep algorithms, namely single sleep and multiple sleep, to determine the time instant to enable micro or pico BSs sleep mode. Finally, we analyze the two proposed algorithms in different HetNet topologies and with different traffic requirements to evaluate the network energy consumption and the savings that the sleep mode can achieve.**

I. INTRODUCTION

Nowadays, we are experiencing a tremendous growth of mobile traffic caused by the evolution of mobile devices (smartphone, tablets, etc.) and by the increased number of broadband services. Such growth is expected to accelerate more in the near future due to the introduction of new cloud-based services and machine-to-machine communications. In order to be able to serve such a big amount of traffic, mobile networks shall increase their capacity.

The huge capacity demand opens two main issues: the cost of the necessary network infrastructure and its environmental footprint. Both issues can be solved by designing an energy efficient mobile network: the decrease of the network energy consumption will result in lower operational cost for the infrastructure and lower greenhouse gas (GHG) emissions.

Macro sites are very difficult and expensive to deploy and operate, especially in urban environments. Because of this, heterogeneous networks (HetNets) are foreseen to be the most popular deployment option in the short and mid term future. HetNets are multi-tier radio access networks in which micro and/or pico/femto cells are overlaying the macros, as shown in Figure 1. Macro Base Stations (BSs) are used as a baseline and provide uniform coverage. Micro and pico/femto (often also referred to as small) cells are equipped with lower power BSs which are deployed in hotspots to increase capacity, or in dead spots unreachable by macro BSs in order to increase coverage. Macro BSs are deployed outdoor, normally above the rooftop level. On the other hand, small BSs are normally deployed below the rooftop level; when outdoor, they are often placed over lampposts or street furniture, and when indoor they are typically installed by the end-users in residential or enterprise settings.

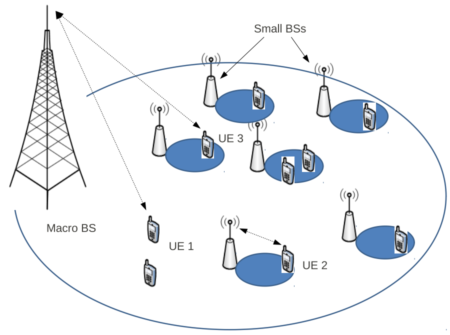

Fig. 1. HetNet scenario with macro cell as baseline and small cells as capacity or coverage cells.

HetNets are more energy efficient than macro-only deployment of the same capacity, due to the lower power consumption of the small cells [1]. Hence, the use of HetNets instead of macro BSs alone can already achieve some energy savings. Additionally, a recent approach for achieving more energy efficiency and hence enjoy more substantial energy savings in HetNets is to make the network energy consumption mimic the traffic dynamics. In fact, network deployments are dimensioned to provide a capacity that is sufficient to handle traffic peaks, and it has been observed that, because of this dimensioning, network equipment spends most of its time (and hence most of its energy) being turned on with a very low or even zero traffic load [2]. Hence, a promising solution is to dynamically put some network elements to sleep during periods of low traffic load, so that the network operates with the smallest subset of network elements that is sufficient to handle the traffic load at a given time, while the rest of the network equipment is kept in a low energy consuming state (called sleep mode), or even switched-off.

In a standard cellular network, the most energy-hungry network equipment is the BS, which usually consumes up to the 80% of the total network energy consumption [3]. Thus, in this paper we study BS sleep solutions to decrease the energy consumption of a HetNet. In particular, we design a model to analyze the energy consumption of LTE, and present two sleep algorithms, namely *multiple sleep* and *single sleep*, which are evaluated in different traffic conditions and for different radio access network topologies.

We note that there are several previously published papers, such as for example [4], [5] and [6], which already studied the BS sleep mode in macro cell scenarios, where it is combined with cell zooming to assure coverage to mobile users. However, only a few papers considered the HetNet scenario. Among these, we cite [7], where the authors apply their general energy model also to a HetNet, and evaluate the energy savings in a urban scenario. However, [7] does not consider that:

- the energy consumed by macro cell is not constant, but rather variable with the traffic load (approximatively linearly);
- when a small cell is switched off, the macro cell assumes the load of that small cell, hence the macro cell energy consumption increases.

The model proposed in this paper overcomes this limitation by explicitly considering the aforementioned aspects, and thus allows to perform a more realistic analysis of the performance of BS sleep algorithms in HetNet scenarios.

II. System Model

A. Traffic Model

Let us consider a site covered by one macro cell and N small cells as in Figure 1.

Let $t \in [0, 24]$ be the time of the day in hours, and let $f(t)$ be the daily traffic pattern in the site, normalized with respect to the peak traffic. We adopt the traffic model of [8], which is representative of typical traffic. According to this model, $f(t)$ has the peak at $t = 0$ and $t = T$, and is symmetric with respect to $T/2$, with $T = 24$.

Since such traffic has to be served by one macro and N overlaying small cells in our scenario, we can write:

$$f(t) = f_M(t) + \sum_{i=1}^{N} f_{S_i}(t) \tag{1}$$

where $f_M(t)$ is the macro generated traffic, i.e., the traffic generated by users that are in the coverage area of the macro cell but not in the coverage area of any small cell (e.g., UE 1 in Figure 1), and $f_{S_i}(t)$ is the i-th component of the small cell generated traffic, i.e., the traffic generated by those users that are in coverage of both the i-th small cell and the macro cell (e.g., UE 2 and UE 3 in Figure 1).

Let us assume that the macro and small cell generated traffic have the same pattern as the traffic profile of the entire site, but scaled down by a factor θ_M and θ_{S_i}, respectively, for the macro and the i-th small cell. We can thus write that $f_M(t) = \theta_M f(t)$ and $f_{S_i}(t) = \theta_{S_i} f(t)$, with $0 \leq \theta_M, \theta_{S_i} \leq 1$.

Let C_M represent the maximum normalized capacity of the macro cell, i.e., the maximum fraction of the site traffic that the macro cell can handle. We assume that $\theta_M \leq C_M$. We define $\hat{\ell} = \theta_M / C_M$, where $\hat{\ell} \in [0, 1]$ represents the maximum expected load level of the macro in the case it serves all the macro generated traffic but none of the small cell generated traffic.

B. Energy Model

Taking into account the power consumption of different LTE BSs introduced in [9], we derive an energy model based on the following assumptions:

- the power consumption of a macro BS is equal to $a\ell + W_M$, where $\ell \in [0, 1]$ is the traffic load of the macro BS normalized to its maximum capacity, and W_M is the power consumption when $\ell = 0$;
- the power consumption of a small BS power consumption is constant (independent from the traffic load variations) and equal to W_S.

A qualitative representation of this power consumption model is provided in Figure 2.

In the remainder of this section, we will determine a formulation for the daily energy consumption E^{on} and E^{sleep}, respectively, of the always on (no sleep) and of the sleep approach.

1) Always-on model: The energy E_M^{on} and E_S^{on} consumed respectively by the macro cell and the small cells in one period T can be written as follows:

$$\begin{aligned} E_M^{\text{on}} &= \int_0^T \left(a \frac{f_M(t)}{C_M} + W_M \right) dt \\ &= a \int_0^T \frac{\theta_M}{C_M} f(t) dt + W_M T \end{aligned} \tag{2}$$

$$E_S^{\text{on}} = N E_s T \tag{3}$$

The daily energy consumption E^{on} of the site is the sum of E_M^{on} and E_S^{on}:

$$E^{\text{on}} = a \int_0^T \frac{\theta_M}{C_M} f(t) dt + W_M T + N W_S T \tag{4}$$

2) Sleep mode model: Let τ_i be the time instant in which the i-th small BS is slept. Without loss of generality, we assume that $\tau_i \leq \tau_j \, \forall i < j$. Let W_0 denote the power consumed by a small BS when sleeping; W_0 is equal to zero if the BS is completely switched off, otherwise it has a value > 0 that depends on how many transmitting components are deactivated during low traffic periods, as described in [10] and [11]. Due to the symmetry of $f(t)$, let us consider only the time period between 0 and $T/2$. Hence the power consumption

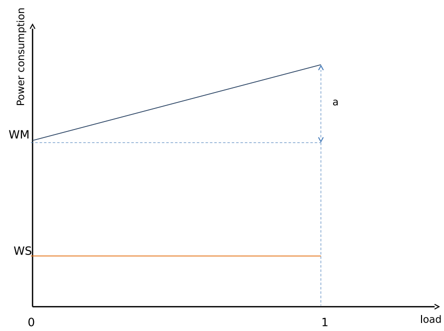

Fig. 2. Power consumption of macro and small BS as a function of the traffic load.

$W_{S_1}^{\text{sleep}}(t)$ of the first small cell can be expressed as a function of the time t as follows:

$$W_{S_1}^{\text{sleep}}(t) = \begin{cases} W_S & t < \tau_1 \\ W_0 & \tau_1 \leq t \leq T/2 \end{cases} \tag{5}$$

When a small cell is in sleep mode, all the traffic it served has to be handed over to the macro cell. As a side effect, the energy consumption of the macro BS will increase by an amount depending on the volume of the new traffic being handled. Then the power consumed by the macro BS after the first small BS is slept and before the second one is slept can be written as:

$$W_M^{\text{sleep}}(t) = a\frac{\theta_M + \theta_{S_1}\beta_1}{C_M} f(t) + W_M,\ \tau_1 \leq t < \tau_2 \tag{6}$$

where β_1 is a parameter representing the different weight on network resource utilization that the handed over traffic has for the macro cell, which is mainly due to the different radio propagation environment.

Generalizing (5), (6) for the i-th sleeping small cell, they become:

$$W_{S_i}^{\text{sleep}}(t) = \begin{cases} W_S & 0 \leq t < \tau_i \\ W_0 & \tau_i \leq t \leq T/2 \end{cases} \tag{7}$$

$$W_M^{\text{sleep}}(t) = \frac{a}{C_M}\left(\theta_M + \sum_{j=1}^{i}\theta_{S_j}\beta_j\right) f(t) + W_M, \qquad \tau_i \leq t < \tau_{i+1} \quad \forall i = 0, ..., N \tag{8}$$

where $\tau_0 = \theta_0 = \beta_0 = 0$ and $\tau_{N+1} = T/2$.

Then, the energy consumed in the period T by the entire site is:

$$\begin{aligned} E^{\text{sleep}} &= 2\int_0^{T/2}\left(W_M^{\text{sleep}}(t) + \sum_{i=0}^{N} W_{S_i}^{\text{sleep}}(t)\right) dt \\ &= 2\sum_{i=0}^{N}\int_{\tau_i}^{\tau_{i+1}}\left\{\frac{a}{C_M}\left(\theta_M + \sum_{j=0}^{i}\theta_{S_j}\beta_j\right) f(t) + W_M\right\} dt \\ &\quad + 2W_S\sum_{i=1}^{N}\tau_i + 2\sum_{i=1}^{N} W_0(T/2 - \tau_i) \end{aligned} \tag{9}$$

We note that (9) has five main components:

1) $2a\frac{\theta_M}{C_M}\int_0^{T/2} f(t)dt$: energy consumed by the macro to serve its portion of traffic;
2) $W_M T$: energy consumed by the macro just to stay turned on;
3) $\frac{2a}{C_M}\sum_{i=0}^{N}\int_{\tau_i}^{\tau_{i+1}}\sum_{j=0}^{i}\theta_{S_j}\beta_j f(t)dt$: energy consumed by the macro to serve small BSs traffic when they are sleeping;
4) $2W_S\sum_{i=1}^{N}\tau_i$: energy consumed by the small BSs while turned on;
5) $2\sum_{i=1}^{N} W_0(T/2 - \tau_i)$: energy consumed by the small BSs while in sleep mode.

III. Sleep Algorithms

A sleeping algorithm has to define the time instants in which the N small cells are going to sleep (also referred to as sleep times in the following), so as to reduce the energy consumption of the whole system, while at the same time maintaining the traffic of the active users.

A. Multiple sleep algorithm

This scheme defines the value of the sleep time (τ_i) for every single small BS. Without loss of generality, let us consider that $\theta_{S_1} \leq \theta_{S_2} \leq ... \leq \theta_{S_N}$. Two conditions must be respected to determine the time instants τ_i: the min-energy and the capacity condition.

1) Min-energy condition: $f(t)$ is strictly decreasing in the interval $[0, T/2]$ (mostly assumed in the literature, such as in [7], [8] or [12]), so E^{sleep} is a convex function of τ_i. Hence, to determine the local minima of (9), we have to calculate the values of τ_i^* so that $\frac{\partial E^{\text{sleep}}}{\partial \tau_i} = 0, \forall i = 1, ..., N$. At the first sleep time τ_1 the following condition must be satisfied:

$$W_S - \frac{a}{C_M}\theta_{S_1}\beta_1 f(\tau_1^*) - W_0 = 0 \tag{10}$$

or, equivalently,

$$W_S - W_0 = \frac{a}{C_M}\theta_{S_1}\beta_1 f(\tau_1^*) \tag{11}$$

which means that at time τ_1^* the energy saved by putting the first small BS to sleep (left side of (11)) is equal to the increase in energy consumption of the macro BS due to the additional traffic from the slept small BS (right side of (11)). We note that at any time $t > \tau_1^*$ the macro BS will consume less energy than at time τ_1^* because of the assumption that $f(t)$ is strictly decreasing. Thus, we have:

$$\tau_1^* = f^{-1}\left(\frac{(W_S - W_0)C_M}{a\theta_{S_1}\beta_1}\right) \tag{12}$$

Generalizing for the i-th sleeping BS, we have:

$$\tau_i^* = f^{-1}\left(\frac{(W_S - W_0)\theta_M}{a\sum_{j=1}^{i}\theta_{S_j}\beta_j}\right) \tag{13}$$

We call (13) min-energy condition.

2) Capacity condition: On the other hand, at the time instant τ_1^{**} at which the macro BS starts having the necessary resources to handle the new incoming traffic from the first sleeping small cell, the following condition must be satisfied:

$$f_M(\tau_1^{**}) + f_{s1}(\tau_1^{**}) = (\theta_M + \theta_{S_1}\beta_1)f(\tau_1^{**}) = C_M \tag{14}$$

Generalizing, the time instant τ_i^{**} at which the macro BS starts having the necessary resources to handle the traffic for the i-th small cell can be determined as:

$$\tau_i^{**} = f^{-1}\left(\frac{C_M}{\theta_M + \sum_{j=1}^{i}\theta_{S_j}\beta_j}\right) \tag{15}$$

We call (15) capacity condition.

Finally, the sleep time τ_i for the i-th small BS has to satisfy both the min-energy and the capacity conditions, i.e.:

$$\tau_i = \max_i(\tau_i^*, \tau_i^{**}) \tag{16}$$

TABLE I
DENSITY OF MACRO AND PICO BSS

System Capacity ($GB/h/km^2$)	Micro Density (BSs/km^2)	Pico Density (BSs/km^2)
50	10	35
100	20	190
150	40	300
200	100	500
250	200	1000

B. Single sleep algorithm

This scheme triggers schedules the sleep of all the N small BSs together in a single event. In this case $\tau_1 = \tau_2 = ... = \tau_N = \tau$.

Then (9) becomes:

$$E^{\text{sleep}} = a \int_0^T f(t)dt + W_M T + \frac{a}{C_M} \sum_{i=1}^{N} \theta_{S_i} \beta_i \int_\tau^T f(t)dt + N W_S \tau + 2N W_0 (T/2 - \tau) \quad (17)$$

The min-energy condition becomes:

$$\tau^* = f^{-1} \left(\frac{N(W_S - W_0)C_M}{a \sum_{i=1}^{N} \theta_{S_i} \beta_i} \right) \quad (18)$$

whereas the capacity condition is:

$$\tau^{**} = f^{-1} \left(\frac{C_M}{\theta_M + \sum_{i=1}^{N} \theta_{S_i} \beta_i} \right) \quad (19)$$

Finally, the value of τ is given by:

$$\tau = \max(\tau^*, \tau^{**}) \quad (20)$$

IV. EVALUATION RESULTS

We now consider specific values of the parameters introduced in sections II and III, and evaluate the daily network energy consumption of the different sleep algorithms applied to various network topologies.

A. Reference Scenarios

In our case study, the macro BSs provide baseline coverage and capacity, and two alternative types of small cell overlays provide additional capacity:

1) micro overlay, in which the capacity cells are micro BSs;
2) pico overlay, in which the capacity cells are pico BSs.

The density of micro and pico BSs in a macro cell depends on the demanded capacity per km^2. The number of micro and pico BSs for a given capacity has been derived from [13], which studies different network densification alternatives for downlink LTE. The values used in our study are summarized in table I. The baseline is given by 14 macro BSs/km^2 (corresponding to a capacity of $39\,GB/h/km^2$), which we also derived from [13].

We considered a trapezoidal function as a special example of the daily traffic pattern $f(t)$, with maximum equal to 1

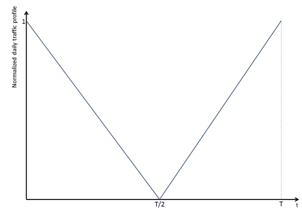

Fig. 3. Trapezoidal traffic pattern used for the evaluation.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
SNR at cell edge	-5dB
Antenna Height (macro)	40m
Antenna Height (micro/pico)	5m
Propagation Model	Okumura-Hata dense urban
W_M	800W
a	500W
W_S (micro)	130W
W_S (pico)	13W
W_0 (micro)	39W
W_0 (pico)	4.3W
$\hat{\ell}$	0.8
$\beta_1 = ... = \beta_N$	1.186

at the peak hour, a slope equal to $2/T$ and symmetric with respect to $T/2$; this function is shown in Figure 3.

B. Resource Utilization in Macro and Small BS

The utilization of radio resources is different in macro and small cells, mainly because their communications experience different propagation conditions, which in turn affects the choice of the modulation and coding scheme. In fact, small BSs have lower output power, are located in the street furnitures, like lampposts, and closer to the users; whereas macro BSs have higher output power but are located in the rooftops, and are often more distant from the users. All these factors give a different distribution of the spectral efficiency η_M and η_S of macro and small cells respectively, measured in bit/Hz.

To account for these factors, we calculate the β_i factor (previously introduced in our model) as:

$$\beta_i = \beta = \frac{E[\eta_S]}{E[\eta_M]}, \forall i \quad (21)$$

where η_M and η_S have been obtained via Monte Carlo simulations by randomly placing 1 million users in both a small cell and macro cell, using the parameters in Table II, and evaluating for each user the spectral efficiency corresponding to the modulation and coding scheme selected by the Adaptive Modulation and Coding model proposed in [14].

C. Results Analysis

We now analyze the results provided by our model when the scenario parameters of table I and II are considered.

The aim of our analysis is threefold: (i) studying the energy consumption of the two different densification scenarios (micro and pico overlays), (ii) analyzing the savings achieved by enabling the small BS sleep mode, (iii) investigating the impact of the modeling assumptions for the macro BS power

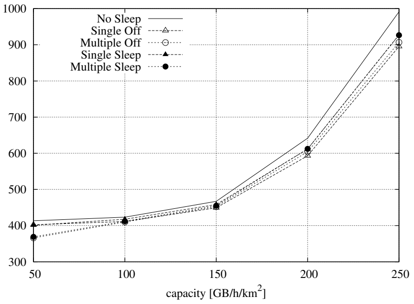

Fig. 4. Energy consumed in micro overlay scenario varying the capacity requirements. Single and multiple sleep algorithms are shown in the figure. The cases of switched-off (off) and slept (sleep) BS are also illustrated.

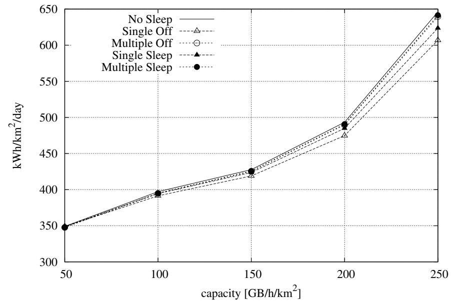

Fig. 5. Energy consumed in pico overlay scenario varying the capacity requirements. Single and multiple sleep algorithms are shown in the figure. The cases of switched-off (off) and slept (sleep) BS are also illustrated.

consumption, in particular with respect to its dependency on the traffic load.

Figures 4 and 5 show the energy per km^2 consumed in one day for the two densification scenarios varying the capacity requirements. Single and multiple sleep algorithms are depicted in the graphs, as well as the cases in which the BSs are switched off (off) or slept (sleep). The values of θ_M, W_0, W_M, W_S used for macro, micro and pico BSs are listed in Table II.

We notice that the two overlays consume a comparable amount of energy up to a required capacity of $100\,GB/h/km^2$: the lower number of deployed micro BSs produces a similar system energy utilization to the pico overlay, despite the differences in the energy consumption of the two types of devices (i.e., micro and pico BS). When the capacity requirement is higher than $100\,GB/h/km^2$, the micro overlay starts consuming more energy: the number of deployed micro BSs is big enough to produce a higher power consumption than the number of pico BSs. In fact, in the case of $250\,GB/h/km^2$, the number of pico and micro BSs per km^2 necessary to serve that amount of traffic is 1000 and 200, respectively and the energy consumed without considering any sleep algorithm is $646\,kWh/km^2/day$ and $991\,kWh/km^2/day$ in the pico and micro overlay, respectively.

When the sleep mode is enabled, we got energy savings up to about 10%, depending on the scenario and system capacity, as it can be appreciated in Figures 4 and 5. Multiple sleep and single sleep algorithms present very similar performance in the studied cases.

For the sake of comprehension, let us consider the specific case of capacity requirement equal to $150\,GB/h/km^2$, which is the most likely forecast for a dense urban scenario in Europe [12]. Such capacity requirement needs 3 micro BSs or 21 pico BSs per macro BS. The system energy consumption is $427\,kWh/km^2/day$ and $467\,kWh/km^2/day$ in pico and micro overlay, respectively and without considering BS sleep mode. The pico overlay achieves $0.6\,(0.7)\%$ of savings for multiple sleep (off) and $0.9\,(2.1)\%$ for single sleep (off) algorithm, whereas the micro overlay gets $3\,(7)\%$ of savings for multiple sleep (off) and $1.8\,(3.8)\%$ for single sleep (off) algorithm. The sleep times identified by the two sleep algorithms are summarized in table III. With this traffic demand,

TABLE III
SLEEP TIMES

	Micro overlay	**Pico overlay**
$\tau_{single}(h)$	9.34	10.14
$\tau_{multiple}(h)$	8.51; 10.26; 10.84	9.56; 10.78; 11.18; 11.39; 11.51; 11.59; 11.65; 11.69; 11.73; 11.76; 11.78; 11.80; 11.81; 11.83; 11.84; 11.85; 11.86; 11.86; 11.87; 11.88; 11.88

the conditions $\tau^* > \tau^{**}$ for single sleep and $\tau_i^* > \tau_i^{**}$ for multiple sleeps always occur for both micro and pico overlay. In other words, the min-energy condition is reached after the capacity condition. In fact, putting a small BS to sleep as soon as the macro BS has the necessary resources to serve the small BS traffic does not result to be the most energy efficient solution for the system. This is due to the additional energy consumption caused to the macro BS to serve the small BS traffic when it is sleeping. For example, let us calculate the cost of moving the first micro BS traffic to the macro BS at $\tau_1^* = 8.51$ hours and $\tau_1^{**} = 5.67$ hours, when using the multiple sleep algorithm. It is equal to $465 \cdot f(t)\ W$, which gives $130\ W$ and $241\ W$ for τ_1^* and τ_1^{**}, respectively.

Similar considerations apply to all the studied cases.

To assess the impact of different modeling assumptions for the macro BS power consumption, we re-evaluate our model in the same scenario just discussed, but assuming a constant macro BS power consumption equal to $1000\ W$, similar to the approach used in [7], instead of the variable power consumption model that we introduced in section II-B. Figures 6 and 7 show the obtained daily energy consumption per km^2. The energy savings appear to be significantly higher (up to 35% and 27% for macro and pico, respectively) for both single and multiple sleep algorithm. Since it is a fact that the power consumption of macro BSs has a significant dependency on the traffic load [12], we argue that assuming a constant macro BS power consumption leads to an overestimation of the energy savings achievable with the use of sleep algorithms. Moreover, designing a sleep algorithm based on such assumption would lead to the determination of small BS sleep time that consider only the capacity condition, which is actually not the most energy efficient approach, as we demonstrated above.

Finally, it is also worth noting that enabling the sleep mode

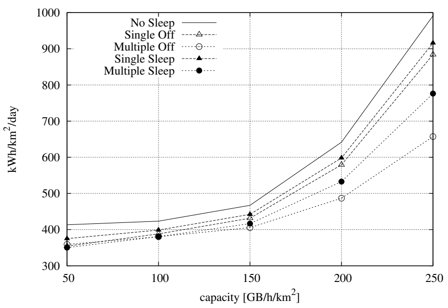

Fig. 6. Energy consumed in micro overlay scenario varying the capacity requirements with constant power macro BS model. Single and multiple sleep algorithms are shown in the figure. The cases of switched-off (off) and slept (sleep) BS are also illustrated.

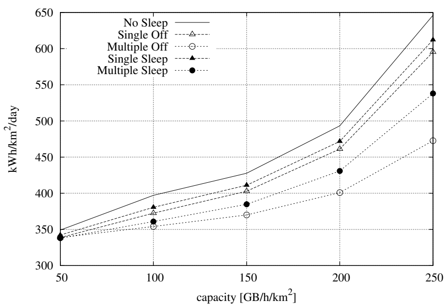

Fig. 7. Energy consumed in pico overlay scenario varying the capacity requirements with constant power macro BS model. Single and multiple sleep algorithms are shown in the figure. The cases of switched-off (off) and slept (sleep) BS are also illustrated.

in a micro overlay results in more energy savings than doing it in a pico overlay: the whole system has an higher decay in energy utilization by sleeping or switching-off a micro BS than a pico BS, due to the higher power consumption figure of micro BSs. Moreover, as expected, the energy saving is higher when the BS is completely off than when it is sleeping. Our results confirm the relevance of investigating mechanisms that reduce the number of transmitting components in a BS in sleep mode, so as to achieve figures closer to the completely off case.

V. Conclusions

In this paper we have presented a model to analyze the energy consumption of a LTE HetNets considering two different types of BSs composing a radio access network (macro and small) and their different radio resource utilization. In particular, the model defines the time instant in which small BSs are allowed to enter the sleep mode. We have also presented two sleep algorithms, namely single sleep and multiple sleep. The first schedules a single event to put to sleep the entire small BSs overlay, whereas the latter defines the time instants in which each single small BS can be put to sleep. Finally, we used our model to carry out a performance evaluation study considering different HetNet topologies (micro overlay and pico overlay) and capacity requirements.

From the results of our analysis, the deployment of a HetNet with pico BSs results the most energy efficient architecture. Moreover, the use of BS sleep mode gives a further reduction in the system energy consumption. Finally, we showed that it is very important to model the dependency of the macro BS power consumption on the traffic load, in order to avoid an overestimation of the energy savings achievable by the use of the sleep mode, and to correctly determine the sleep times.

The achieved results encourage future research work on BS sleep mode and in particular in:

- managing radio resources and mobility in presence of BS sleep mode;
- energy-aware load balancing between macro and small cells;
- reducing the number of BS transmitting components during the sleep periods.

Acknowledgements

This work has been partially funded by the Spanish Ministry of Science and Innovation under grant TEC2011-29700-C02-01 (project SYMBIOSIS) and TEC2010-20823 (project CO2GREEN), by the Generalitat de Catalunya under grant 2009-SGR-940 and the European Community Seventh Framework Programme FP7 through the Integrated Project (IP) COMBO under grant agreement no 317762.

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