

# Multiple Daily Base Station Switch-Offs in Cellular Networks

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**Abstract**—In this paper we study base station sleep modes, which are today considered a viable approach to improve the energy efficiency of cellular access networks, by reducing power consumption in periods of low traffic.

When some base stations are switched off, radio coverage and service provisioning are taken care of by the base stations that remain active, so as to guarantee that service is available over the whole area at all times. This is a realistic assumption in the case of the dense base station layouts of urban areas, which consume most of the network energy.

We develop simple analytical models that allow optimal base station switch-off times to be identified as a function of the daily traffic pattern, in the cases in which either just one switch-off per day is possible (bringing the network from a high-power, fully-operational configuration, to a low-power reduced configuration), or several switch-offs per day are permitted (progressively reducing the number of active base stations and the network power).

We first assume that any fraction of base stations can be switched off, then we consider a realistic case.

We quantify the percentage of energy which can be saved with base station sleep modes, proving that it can be close to 50% of the total network energy consumption.

## I. INTRODUCTION

In the early days of networking, the term *power* was used to identify the ratio of throughput over delay [1], [2], because energy issues did not belong in the networking landscape. Then, cellular networks and battery-operated terminals (most notably mobile phones) came along, and power control (now real power, measured in J/s) became an issue, in order to extend both the distance from the base station at which a terminal could be used, and the battery charge duration (in the early '90s, heavy users carried a spare charged battery in their pocket, to avoid being cut off around noon). Next, sensor networks brought with them the question of power minimization to increase the network lifetime. Still, before the turn of the century, power consumption was not an element of the wired network design space. The first paper that addressed energy issues in fixed networks was [3], where Gupta and Singh investigated the energy consumption of Internet devices, and discussed the impact of sleep modes on network protocols. Since then, the interest in energy-efficient networking has been steadily rising, and the energy issue is now addressed in many papers and research projects, among which we wish to mention TREND (Towards Real Energy-efficient Network Design) [4], the Network of Excellence funded by the European Commission within its 7th Framework Programme, and the Italian

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The directions that are presently pursued to achieve energy efficiency in networking can be grouped in two classes: 1) development of new technologies that reduce energy consumption, and 2) identification of approaches that make the network energy consumption proportional to traffic. The rationale for the second direction derives from the observation that today network equipment exhibits power consumption which is practically independent on load. For example, a base station of a cellular network consumes at zero load about 80-90% of the energy consumption at full load [5].

Approaches that aim at improving the proportionality between the network energy consumption and the network load can be further divided in 2 sub-classes: 2a) development of equipment exhibiting better proportionality of energy consumption to load, and 2b) identification of algorithms that allow the reduction of the functionality of network equipment in periods of low traffic, so as to decrease energy consumption in such periods. The algorithms that received most attention in class 2b are often called speed scaling, and sleep modes. By speed scaling we normally mean that the equipment can operate at different clock rates, with lower rates corresponding to lower power (and lower performance). By sleep modes we mean that in periods of low traffic the network operates with a subset of its equipment, the rest being switched off to save energy.

In the case of cellular networks, the critical equipment for power consumption are base stations (BSs), which, in a normal network, together make up for about 80% of the total energy consumption [6]. In this paper we consider sleep modes for BSs in cellular networks, and we investigate the benefits that can be achieved by switching off a portion of the BSs during periods of low traffic. This means that the cellular access network planning should in the future consist of different layers, which correspond to network configurations planned to serve different levels of traffic. These configurations can be activated according to predefined schedules, or traffic forecasts, or real-time traffic measurements. We compute the maximum amount of energy that can be saved with this approach, and we study the impact of the number of layers. We assume that when some base stations are switched off, radio coverage and service provisioning are taken care of by the base stations that remain active, so as to guarantee that service is available over the whole area at all times. This may be an optimistic assumption in the case of sparse base station layouts

in rural areas, but is on the contrary a realistic hypothesis for the dense layouts of urban areas, which consume most of the network energy.

The fact that BSs are the most energy-greedy components of cellular networks, and are often under-utilized, was realized only few years ago [6], [7], [8], [9]. Since then, several approaches have been pursued to reduce the carbon footprint of BSs, ranging from the use of renewable energy sources [10], to the improvement of hardware components [11], to cell zooming techniques [12], to the adoption of sleep modes. As regards sleep modes, starting from our early works [13], [14], [15], it has been shown that sleep modes adoption for BSs is an efficient solution that allows a significant amount of energy to be saved during low traffic periods. Later, also the authors of [16] showed, using real data traces, that promising potential savings are achievable by turning off BSs during low traffic periods. Recently, in [17] the authors have investigated energy savings in dynamic BS operation and the related problem of user association, showing that their algorithms can significantly reduce the energy consumption. A distributed solution to switch off underutilized BSs when traffic is low, and switch them on when traffic is high, was proposed in [18]; large savings, that depend on temporal-spatial traffic dynamics, are shown to be possible.

Differently from most previous works, but expanding our analysis in [14], here we analytically characterize the maximum energy savings that can be achieved under a given traffic profile. In particular, we analytically show that the optimal trade-off between energy savings and complexity in network management is obtained when only few switch-off configurations per day are allowed, and BSs are switched-off in increasing order of load. These results are also corroborated by a case-study analysis.

The main differences between this work and [14] are the following. First, in [14] we focused on just one switch-off, while in this work we consider the possibility of multiple switch-offs. Second, in [14] we focused on homogeneous networks (i.e., networks where all cells have identical size and traffic pattern), while here we consider also heterogeneous networks (i.e., different cell sizes and traffic patterns). Third, we consider a realistic cell deployment of an operator network, rather than assuming only idealized cell layouts, like in [14].

## II. OPTIMAL SLEEP MODES IN HOMOGENEOUS NETWORKS

We first propose a simple analytical framework to compute the optimal energy savings assuming that one switch-off only is allowed per day (summarizing the results of [14]). Then, we extend our analysis in [14] to the case in which multiple switch-offs are allowed, and we discuss the savings achievable with these schemes under an idealized traffic profile.

### A. One switch-off

Let  $f(t)$  be the daily traffic pattern in a cell, i.e., the traffic intensity as a function of time  $t$ , with  $t \in [0, T]$ ,  $T = 24$  h, and  $t = 0$  the peak hour;  $f(t)$  is normalized to the peak hour traffic, so that  $f(0) = 1$ . As an example, in Fig. 1 we report

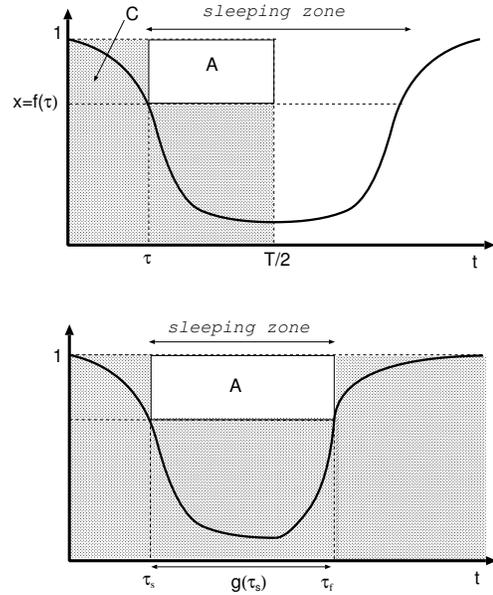


Fig. 1. Traffic intensity during a day: symmetric case (top), and asymmetric case (bottom).

two typical daily traffic patterns, a symmetrical one (top), and an asymmetrical one (bottom). The cellular access network is dimensioned so that at peak traffic a given QoS constraint is met. Clearly, if the QoS constraint is met under peak traffic  $f(0)$ , it is also met for lower values of traffic intensity, and thus during the whole day. We assume that in the considered area all cells have identical traffic patterns, and we thus say that the network is *homogeneous*.

Consider a sleep scheme  $\Phi$  such that, during the low traffic period (called *sleeping zone*), a fraction  $x < 1$  of the cells is active, while the remaining fraction,  $1 - x$ , of the cells (actually, of the respective BSs) is in sleep mode. As was shown in [14], during the sleeping zone, the  $x$  on BSs have to sustain, in addition to their own traffic, the traffic that in normal conditions is taken care of by the  $1 - x$  off BSs; so that their traffic becomes:

$$f^{(\Phi)}(t) = f(t) + \frac{1-x}{x}f(t) = \frac{1}{x}f(t) \quad (1)$$

i.e., they receive  $1/x$  times their own traffic. Thus, to always satisfy the QoS constraint, scheme  $\Phi$  can be applied whenever the traffic is so low that  $f^{(\Phi)}(t)$  is still below 1, that is the peak hour traffic. Starting from the peak hour, with decreasing  $f(t)$ , the earliest time instant  $\tau$  in which  $\Phi$  can be applied is defined by  $f^{(\Phi)}(\tau) = 1$ , so that,

$$\tau = f^{-1}(x) \quad (2)$$

As shown in Fig. 1, the sleeping zone starts in  $\tau$  and lasts for the whole period in which the traffic intensity is below  $f(\tau) = x$ .

For simplicity, let us now focus on a daily traffic pattern that is symmetric around  $T/2$ , i.e., such that  $f(\tau) = f(T-\tau)$  with  $\tau \in [0, T/2]$ , as in the top part of Fig. 1. The duration of the sleeping zone is  $T - 2\tau$ . Denote by  $W$  the power consumption of a BS. The average energy consumed per BS in a day under

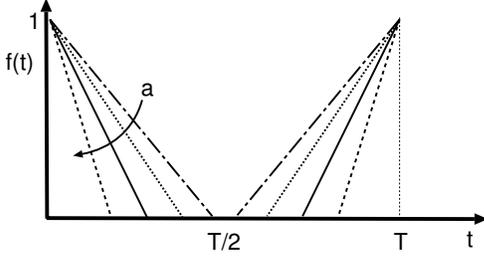


Fig. 2. Trapezoidal traffic pattern.

scheme  $\Phi$  is equal to,

$$C(\tau) = 2W \left[ \tau + f(\tau) \left( \frac{T}{2} - \tau \right) \right] \quad (3)$$

since for a period  $2\tau$  the consumption is  $W$ , and for a period  $2(T/2 - \tau)$  the consumption is a fraction  $x$  of the previous one:  $xW = f(\tau)W$ . The total network saving with respect to an always-on scheme is,

$$S = 1 - \frac{C(\tau)}{WT} \quad (4)$$

When one sleep scheme only is allowed per day, the optimal scheme is the one that can be applied in  $\tau^* \in [0, T/2]$ , with  $\tau^*$  such that the energy consumption  $C(\tau)$  is minimum, and saving is maximum. By assuming that  $f(t)$  is monotonically decreasing in the interval  $[0, T/2]$ , the value of  $\tau^*$  can be obtained from the derivative of  $C(\tau)$ , letting

$$2W \left[ 1 + f'(\tau^*) \left( \frac{T}{2} - \tau^* \right) - f(\tau^*) \right] = 0 \quad (5)$$

A graphical representation of this result is shown in the top part of Fig. 1. The energy consumption is proportional to the shaded area: it is  $W$  for a period  $\tau$ , and  $Wf(\tau)$  for a period  $(\frac{T}{2} - \tau)$ . To minimize energy consumption, the rectangular white area in the figure should be as large as possible.  $C(\tau)$ .

For non-symmetric traffic patterns  $f(t)$ , as in the bottom part of Fig. 1, the optimum scheme can be derived in a similar way by defining the area  $A$  and looking for the value of  $\tau$  that guarantees that  $A$  is the maximum possible one.

*Trapezoidal traffic pattern:* As a special simple example of daily traffic pattern we consider the family of symmetric trapezoidal curves plotted in Fig. 2, with maximum equal to 1 at the peak hour, and different slopes, defined by the angular coefficient  $a$ ,<sup>1</sup>

$$f(t) = \begin{cases} 1 - at & 0 \leq t < 1/a \\ 0 & 1/a \leq t \leq T/2 \end{cases} \quad (6)$$

with  $1/a < T/2$  (a similar derivation is possible for values  $1/a > T/2$ ).

Applying (5), the minimum energy consumption can be achieved for

$$a\tau^* = a \left( \frac{T}{2} - \tau^* \right) \quad (7)$$

<sup>1</sup>Rather than working on a single profile, we consider a family of profiles. In this way, we extend our findings to a generic scenario which is representative of different traffic profiles.

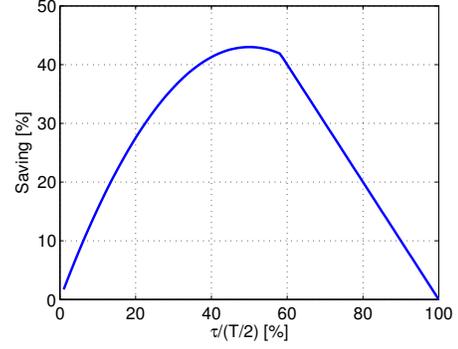


Fig. 3. Trapezoidal traffic pattern: saving with one switch-off scheme.

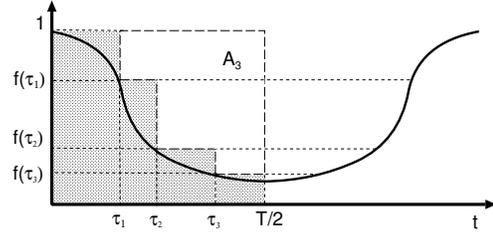


Fig. 4. Example of multiple sleep schemes with  $N=3$ .

so that:

$$\tau^* = \begin{cases} T/4 & \text{if } T/4 < 1/a \\ 1/a & \text{otherwise} \end{cases} \quad (8)$$

It is interesting to observe that, whenever  $1/a > T/4$ , the optimal scheme consists of a 50-50 rule, that uses all BSs in the high-traffic half-day, and turns off a fraction  $aT/4$  of the BSs in the low-traffic half-day.

The resulting maximum network saving with respect to an always-on scheme is,

$$S^* = \begin{cases} \frac{aT}{8} & \text{if } T/4 < 1/a \\ 1 - \frac{2}{aT} & \text{otherwise} \end{cases} \quad (9)$$

which is at least equal to 25%, since  $1/a < T/2$ .

Fig. 3 reports the saving  $S$  for different values of  $\tau$  under the trapezoidal profile with  $a = 0.14$  [1/h]. The saving strongly depends on the values of  $\tau$  and it is larger than 40% for  $\tau = \tau^*$ .

### B. Multiple sleep schemes

Now we study the maximum saving achievable when multiple sleep schemes  $\Phi_i$  (with  $i = 1, \dots, N$ ) are allowed during a day. In particular, given a decreasing traffic profile  $f(t)$ , symmetric around  $T/2$ , we assume that the schemes  $\Phi_i$  are ordered in such a way that the fraction of BSs that is switched off increases with  $i$ . In other words, we assume to switch-off a fraction  $(1 - x_1)$  of BSs at a certain time instant  $\tau_1$ , a fraction  $(1 - x_2)$  at  $\tau_2$ , ...,  $(1 - x_i)$  at  $\tau_i$ , with  $x_1 > x_2 > \dots > x_i$ . As shown in Fig. 4, the area  $A_N$  is now the composition of some rectangular shapes, and can be computed as,

$$A_N(\tau_1, \tau_2, \dots, \tau_N) = \sum_{i=1}^N (\tau_{i+1} - \tau_i)(1 - f(\tau_i)) \quad (10)$$

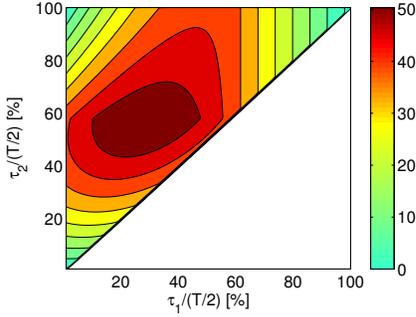


Fig. 5. Trapezoidal traffic pattern: percentage saving, according to the color scale on the right, with double switch-off scheme.

where  $\tau_{N+1} = T/2$ . As for the single switch-off scheme case, the network saving,  $S_N$ , can be maximized by maximizing the area  $A_N$ , i.e., by finding the set of values  $(\tau_1^*, \tau_2^*, \dots, \tau_N^*)$  such that  $\frac{dA_N}{d\tau_i} = 0$ , for  $i = 1, \dots, N$ . Thus, the following system of equations must be solved:

$$-f'(\tau_i)(\tau_{i+1} - \tau_i) + f(\tau_i) - f(\tau_{i-1}) = 0 \text{ with } i = 1, \dots, N \quad (11)$$

with  $\tau_0 = 0$  (so that  $f(\tau_0) = 1$ ) and  $\tau_{N+1} = \frac{T}{2}$ .

An upper bound of the achievable network saving can be obtained by considering that the fraction of BSs that is switched off increases in a continuous way, through infinitesimal increments. In other terms, the upper bound of the area  $A$ , namely area  $A^U$ , can be computed as the complement of the integral of  $f(t)$ ,

$$A^U = \int_0^{T/2} (1 - f(\tau)) d\tau \quad (12)$$

that corresponds to the upper bound of the saving,

$$S^U = \frac{2}{T} \int_0^{T/2} (1 - f(\tau)) d\tau \quad (13)$$

In the following, we start by analyzing the case of two switch-off schemes, i.e.,  $N = 2$ , for the trapezoidal traffic profile. Then, the results obtained for  $N > 2$  are presented. We will refer to optimal saving for  $N$  switch-off schemes by  $S_N^*$ .

*Trapezoidal traffic pattern:* We solve (11) for the trapezoidal traffic pattern and two switch-off configurations ( $N = 2$ ), obtaining the following optimal switch-off time instants  $(\tau_1^*, \tau_2^*)$ :

$$\tau_1^* = \begin{cases} T/6 & \text{if } T/3 < 1/a \\ 1/(2a) & \text{otherwise} \end{cases} \quad (14)$$

$$\tau_2^* = \begin{cases} T/3 & \text{if } T/3 < 1/a \\ 1/a & \text{otherwise} \end{cases} \quad (15)$$

The maximum saving  $S_2^*$  is,

$$S_2^* = \begin{cases} \frac{aT}{6} & \text{if } T/3 < 1/a \\ 1 - \frac{3}{2aT} & \text{otherwise} \end{cases} \quad (16)$$

which is at least equal to 33%, since  $1/a < T/2$ .

Fig. 5 reports  $S_2$  versus  $\tau_1$  and  $\tau_2$  for  $a = 0.14$  [1/h]. The first switch-off configuration is applied at  $\tau_1$ , while the

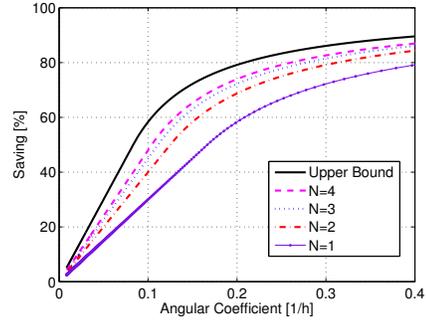


Fig. 6. Trapezoidal traffic pattern: maximum achievable saving for various number of schemes versus the angular coefficient  $a$ .

second one is applied at  $\tau_2$ . Observe that, by definition of the  $\tau_i$ , the white area for which  $\tau_1 \geq \tau_2$  corresponds to non admissible points. Moreover, the maximum saving corresponds to the configurations applied at the optimal time instants  $\tau_1^*$  and  $\tau_2^*$ . As expected, the maximum saving with two schemes, that is around 50%, is larger than the one of single switch-off case (Fig. 3).

Fig. 6 shows the maximum network saving  $S_N^*$  versus the angular coefficient  $a$  for some values of  $N$ ; the upper bound  $S^U$  is also reported. Clearly, the saving increases with  $N$ , reaching the upper bound for  $N \rightarrow \infty$ . However, while the two switch-off scheme achieves significant additional saving with respect to the single switch-off case, the further increase of  $N$  to 3, 4, leads to marginal further improvements. This means that  $N = 2, 3$  is enough to achieve saving that is close to the upper bound. Higher values of  $N$  bring small additional improvements only, while introducing higher complexity in network management.

### III. HETEROGENEOUS NETWORKS

We now consider the case of *heterogeneous* networks, i.e., networks in which cells of different size and load coexist (possibly covered by BSs with different technologies). In particular, we consider a scenario in which an umbrella (macro) cell provides coverage over an area, and  $K$  micro-cells are deployed to provide additional capacity. To save energy, micro-cells can be put to sleep when their traffic is low and can be carried by the macro-cell.

We assume that the traffic profile  $f(t)$  of the umbrella cell is decreasing with  $t$  and is symmetric around  $T/2$ . The micro-cells have the same traffic profile shape as the macro-cell,  $f(t)$ , since this is given by the typical human behavior that is assumed to be uniform in a given area; however, based on size and user density, the shape can be scaled down of a given factor, i.e., micro-cell  $i$  supports a traffic that is  $\alpha_i f(t)$ , with  $\alpha_i < 1$ . Without loss of generality, let  $\alpha_1 < \alpha_2 < \dots < \alpha_K$ .

Let  $\mathcal{O}$  be the ordering in which the micro-cells are switched off, and let it be described by the mapping function,  $o(\cdot)$ , so that  $o(i) = j$ , if the  $i$ -th micro-cell to be switched off is micro-cell  $j$ . The time instant in which the first cell,  $o(1)$ , can be switched off is given by the instant  $\tau_1$  in which the macro-cell can carry the traffic of micro-cell  $o(1)$  in addition to its

own traffic. That is, when the following condition holds,

$$\begin{aligned} f(\tau_1) + \alpha_{o(1)}f(\tau_1) &= 1 \\ \tau_1 &= f^{-1}\left(\frac{1}{1 + \alpha_{o(1)}}\right) \end{aligned} \quad (17)$$

Similarly, the  $i$ -th switch-off instant corresponds to the instant in which the macro-cell can carry its own traffic and the traffic of the micro-cells  $o(1), o(2), \dots, o(i)$ , that is,

$$\tau_i = f^{-1}\left(\frac{1}{1 + \sum_{j=1}^i \alpha_{o(j)}}\right) \quad (18)$$

Assuming that the micro-cells consume  $W$  watts each, and that the macro-cell consumes  $W_M$ , the network daily consumption is given by,

$$\begin{aligned} C &= W_M T + 2W \sum_{i=1}^K \tau_i \\ &= W_M T + 2W \sum_{i=1}^K f^{-1}\left(\frac{1}{1 + \sum_{j=1}^i \alpha_{o(j)}}\right) \end{aligned} \quad (19)$$

since the macro-cell is always on and consumes  $2W_M T/2$  per day, while micro-cell  $o(i)$ , that switches off at time  $\tau_i$  consumes an amount of power equal to  $2W\tau_i$ . It can be shown that the optimal ordering that guarantees the maximum saving consists in switching off micro-cells according to their load from the least-loaded to the most loaded.

#### IV. CASE STUDY

We now consider traffic profiles measured from an anonymized cellular operator, whose data are available online (see [19]). In particular, we focus on two profiles: the first one, namely the *weekday* profile, is chosen as the most-loaded day of the most-loaded BS among the available profiles; the second one, the *weekend* profile, is measured on Sunday for the same BS. Both profiles are reported in Fig. 7. Traffic is normalized to the weekday peak hour, that occurs around 7pm. Traffic is lower in the weekend profile, with a peak around 5pm, about 40% lower than the weekday peak. For both profiles, traffic is very low from late night to early morning, i.e., from 1am to 9am. Similar to the synthetic profile considered in Sec. II, the profiles have wide off-peak periods, short peak periods, and steep transitions. This confirms that the results presented in Sec. II, while being derived with synthetic traffic, can be considered representative of real profiles.

We focus on a case study given by a realistic cell deployment. We consider a portion of the central area of the city of Munich, Germany, which corresponds to a square of 800 x 800 m comprising 1 macro-cell, 8 micro-cells, and 10 femto-cells. Femto-cells are deployed to provide additional capacity during peak hours in indoor environments. However, we do not consider them in the sleep schemes, since they consume a negligible amount of power (around 0.02 watts). The micro-cells are served by isotropic antennas, each with transmission power of 1 W, while the macro-cell has a tri-sectorial antenna with emitted power of 40 W. We assume that the total power consumption of the macro-cell is seven times higher than the

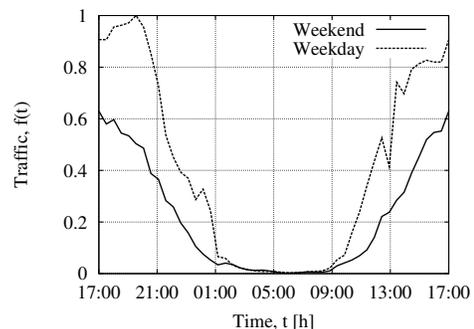


Fig. 7. Traffic intensity: weekday and weekend profiles.

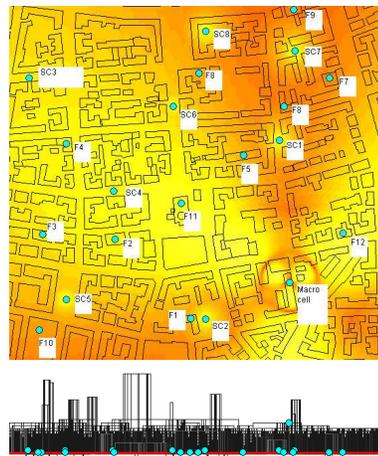


Fig. 8. Case study: Map with cell identifiers (SC = micro cell). Aerial view (top) and side view (bottom).

one of a micro-cell [20]. For example, the macro-cell can be assumed to consume 1400 W and a micro-cell 200 W. Moreover, we assume that power consumption is negligible when the BS is powered off. Fig. 8 presents a map of the considered area (top), together with a side view (bottom).

The coverage is computed from the signal strength received on the users' pilot channel. To estimate the channel conditions, i.e., the path losses, we use the results of a tool developed by Alcatel-Lucent, called Wireless System Engineering (WiSE) [21], that is based on ray-tracing techniques. We refer the reader to [22] for further details on coverage computation.

The network is planned assuming that i) users are uniformly distributed in the area, ii) the generated traffic follows the weekday profile of Fig. 7, and iii) at the peak, the most loaded cell carries traffic equal to 1. During low traffic periods, micro-cells are switched off and the macro-cell acts as an umbrella cell. We assume that the macro-cell guarantees full coverage, even when all the other cells are put in sleep mode.

We now compute the energy saving achievable with several switch-off schemes. Table I summarizes the network saving  $S$  obtained under different configurations. Significant saving (41%) can be achieved with the single switch-off, while the saving increment is marginal as the number of switch-offs increases. These results corroborate the findings of Section II.

Finally, Fig. 9 shows the number of active micro BSs versus time, considering the weekday profile: the case of single, double, and triple switch-offs, are reported. For completeness, the curve obtained with the optimal ordering is also shown

TABLE I  
CASE STUDY: SAVINGS WITH DIFFERENT SWITCH-OFF SCHEMES  
(WEEKDAY PROFILE)

Switch-off scheme	$S$ [%]
Single (8/9)	40.8
Double (5/9)-(8/9)	45.7
Triple (3/9)-(5/9)-(8/9)	46.9
Maximum	48.7

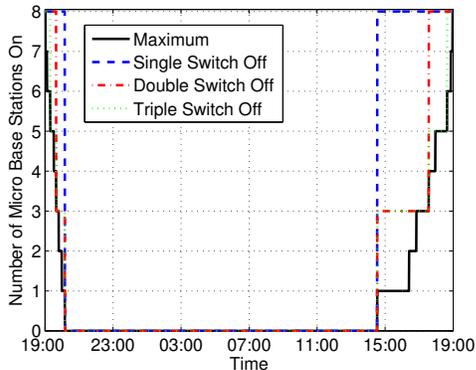


Fig. 9. Number of active micro BSs versus time for different switch-off schemes.

(labeled with 'Maximum'): this represents a lower bound on the minimum number of active BSs that allows the network to achieve the maximum saving by switching off all the cells except the macro in the best order, i.e., from the least loaded to the most loaded.

## V. CONCLUSIONS

In this paper we investigated the energy saving that can be achieved in cellular access networks by optimizing the use of sleep modes according to the daily traffic variations.

Our study adopts several simplifying assumptions about network traffic and technology, the most important of which are: i) users are uniformly distributed over the area served by the cellular access network (this makes traffic uniform across cells, if cells have the same area), and ii) when a cell is switched off, coverage can be filled by its neighbors, which also absorb the traffic.

In this setting, we derived expressions for the energy saving as a function of the daily traffic pattern, assuming first that only one switch-off is allowed per day, and then considering multiple switch-offs per day.

The achievable savings were computed for a realistic cell layout, obtaining several interesting insights. First of all, we computed potential energy savings up to almost 50%. This is an important signal that sleep modes can indeed be a useful tool for energy-efficient networking. Second, we have shown that significant savings can be achieved with only one switch-off per day, while the benefit of multiple switch-offs is minor. This is also an important indication, because it shows that most of the gains can be obtained with limited effort on the side of network management.

Our results provide a tangible incentive for cellular network operators to implement sleep modes in their networks.

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## REFERENCES

- [1] A. Giessler, J. Haenle, A. Koenig, E. Pade, *Free buffer allocation: An investigation by simulation*, Computer Networks, Vol.2, n.3, July 1978, pp. 191-208.
- [2] L. Kleinrock, *Power and Deterministic Rules of Thumb for Probabilistic Problems in Computer Communications*, ICC 79, Boston, MA, USA, June 1979.
- [3] M. Gupta, S. Singh, *Greening of the Internet*, ACM SIGCOMM 2003, Karlsruhe, Germany, August 2003.
- [4] TREND Project, <http://www.fp7-trend.eu>.
- [5] K. Son, B. Krishnamachari, *SpeedBalance: Speed-Scaling-Aware Optimal Load Balancing for Green Cellular Networks*, IEEE INFOCOM Mini-conference 2012, Orlando, FL, USA, March, 2012.
- [6] J.T. Louhi, *Energy efficiency of modern cellular base stations*, INTELEC 2007, Rome, Italy, September-October 2007.
- [7] H. O. Scheck, J. Louhi, *Energy Efficiency of Cellular Networks*, W-GREEN 2008, Lapland, Finland, September 2008.
- [8] Global Action Plan, *An inefficient truth*, <http://www.globalactionplan.org.uk/>, Global Action Plan Rep., 2007.
- [9] M. Hodes, *Energy and power conversion: A telecommunication hardware vendor's perspective*, [http://www.peig.ie/pdfs/ALCATE~1.PPT](http://www.peig.ie/pdfs/ALCATE%201.PPT), Power Electronics Industry Group, 2007.
- [10] *Bi-annual Report November 2010*, Green Power for Mobile, GSMA.
- [11] H. Claussen, L. T. W. Ho, and F. Pivit, *Effects of joint macrocell and residential picocell deployment on the network energy efficiency*, IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2008, Cannes, France, September 2008.
- [12] Z. Niu, Y. Wu, J. Gong, Z. Yang, *Cell zooming for cost-efficient green cellular networks*, IEEE Communication Magazine, Vol. 48, n. 11, pp. 74-79, November 2010.
- [13] L. Chiaraviglio, D. Ciullo, M. Meo, M. Ajmone Marsan, *Energy-Aware UMTS Access Networks*, W-GREEN 2008, Lapland, Finland, September 2008.
- [14] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, *Optimal Energy Savings in Cellular Access Networks*, GreenComm'09 - 1st International Workshop on Green Communications, Dresden, Germany, June 2009.
- [15] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, *Energy-Efficient Management of UMTS Access Networks*, ITC 21 - 21st International Teletraffic Congress, Paris, France, September 2009.
- [16] E. Oh, B. Krishnamachari, X. Liu, Z. Niu, *Toward dynamic energy efficient operation of cellular network infrastructure*, IEEE Communication magazine, Vol. 49, n. 6, pp. 56-61, June 2011.
- [17] K. Son, H. Kim, Y. Yi and B. Krishnamachari, *Base Station Operation and User Association Mechanisms for Energy-Delay Tradeoffs in Green Cellular Networks*, IEEE Journal on Selected Area in Communications: Special Issue on Energy-Efficient Wireless Communications, 2011 (to appear).
- [18] C. Peng, S. B. Lee, S. Lu, H. Luo, H. Li, *Traffic-Driven Power Saving in Operational 3G Cellular Networks*, ACM MobiCom 2011, Las Vegas, Nevada, USA, September 2011.
- [19] *Normalized cellular traffic trace during one week*, data available at: <http://anrg.usc.edu/www/index.php/Downloads>.
- [20] G. Auer, V. Giannini, I. Godor, P. Skillermarck, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, C. Desset, O. Blume, *Cellular Energy Efficiency Evaluation Framework*, GreeNet workshop, in proc. of VTC Spring 2011.
- [21] S. Fortune et al., *WiSE Design of Indoor Wireless Systems: Practical Computation and Optimization*, IEEE Computational Science & Engineering, vol. 2, no. 1, pp. 58-68, spring 1995.
- [22] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, *Switch-Off Transients in Cellular Access Networks with Sleep Modes*, GreenComm 4, Kyoto, Japan, June 2011.