Optimal Energy Savings
in Cellular Access Networks

Marco Ajmone Marsan[1,2], Luca Chiaraviglio[1], Delia Ciullo[1], Michela Meo[1]
1) Electronics Department, Politecnico di Torino, Italy
2) IMDEA Networks, Madrid, Spain

Abstract—In this paper we study with simple analytical models the energy-aware management of cellular access networks, trying to characterize the amount of energy that can be saved by reducing the number of active cells during the periods when they are not necessary because traffic is low. When some cells are switched off, radio coverage and service provisioning are taken care of by the cells that remain active, so as to guarantee that service is available over the whole area. We show how to optimize the energy saving, first assuming that any fraction of cells can be turned off, and then accounting for the constraints resulting from the cell layout.

I. INTRODUCTION

According to [1] "the CO_2 emissions of the ICT industry alone exceed the carbon output of the entire aviation industry." This surprising finding is just one of the many signals that ICT is becoming a major component of the world energy consumption budget. Current estimates indicate that ICT is responsible for a fraction of the world energy consumption ranging between 2% and 10% [2]. The main energy consumers in the ICT field are large data centers and server farms, and telecommunication networks, including wired and wireless telephony networks, as well as the Internet. In Italy, Telecom Italia, the incumbent telecommunications operator, consumes more than 2 TWh a year, representing about 1% of the total national energy demand, second only to the Italian railway system [3]. The energy consumption of ICT is expected to grow even further in the future. Estimates forecast a ten-fold increase in the energy consumed by the telecommunications sector in Italy in the next ten years, the main culprit being customer premises networking equipment.

This situation, coupled with increasing energy costs, has generated a keen interest of telecommunication network operators for energy saving approaches. Efforts will probably focus, at least initially, on the access segment, mainly because there can be found the highest number of elements, so that the energy saved in one access equipment is multiplied by a large factor, with an important contribution to the reduction of the overall network energy consumption. For example, in the case of UMTS, one Node-B consumes around 1500 W (this number may vary between 800 and 3000 W), but altogether these devices contribute between 60 to 80% of the whole network energy consumption [4], [5].

In order to save energy, telecommunication network operators are on the one hand pushing their suppliers to produce more energy parsimonious equipment [6], and on the other hand considering ingenious approaches, like generators located where energy is needed, so that no loss is incurred between producer and consumer. Very recent is the announcement that Ericsson researchers have developed a wind-powered tower for wireless base stations of cellular networks [1].

Local approaches, that aim at reducing the energy consumption of individual network components, can be quite effective. However, global approaches, that consider the entire network energy consumption in the network design, planning, and management phases are a must, for a holistic approach to energy efficient networking.

In this paper we tackle the issue of energy-aware management of cellular access networks, trying to characterize the amount of energy that can be saved by reducing the number of active cells in the access networks during the periods when they are not necessary because the network traffic is low.

The reduction of the traffic in some portions of a cellular network is due to the combination of two effects: i) the typical day-night behavior of users; ii) the daily swarming of users carrying their mobile terminals from residential areas to office districts and back, resulting in the need for large capacity in both areas at peak usage times, but in reduced requirements during the period in which the area is lightly populated (day for residential areas and night for office districts).

When some cells are switched off, we assume that radio coverage and service provisioning can be taken care of by the cells that remain active, possibly with some small increase in the emitted power, so as to guarantee that service is available over the whole area. In our previous work [7] we showed that, in urban UMTS scenarios, in the few cases in which the emitted power must be increased, this increase is negligible (a few watts) if compared to the total Node-B energy consumption and does not induce any electromagnetic exposure limit violation.

Our energy-saving approach assumes that the original network dimensioning is essentially driven by traffic demands, as it normally happens in metropolitan areas, comprising a large number of small cells. This planning becomes excessive in the regions that for some time are subjected to a traffic much lower than the peak. Assume that during peak traffic periods an area is served by K cells, each one with traffic f, achieving the desired quality of service (QoS). When the traffic declines, say to xKf (with $x < 1$) in the whole area, just xK cells are necessary to obtain the same QoS, provided that electromagnetic coverage is preserved. Thus $(1 - x)K$ cells can be switched off out of K, saving a fraction of energy

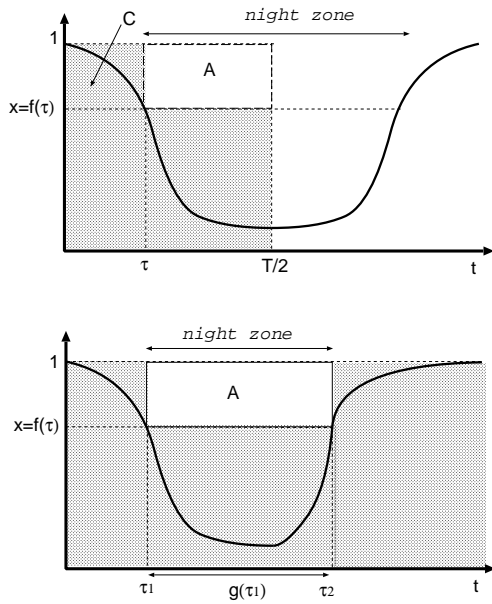Fig. 1. Traffic intensity during a day: symmetric case (top), and asymmetric case (bottom)

equal to $(1-x)$. That is, when $(1-x)K$ cells are switched off, the power consumption reduces to a fraction x of the original. The choice of the proper fraction x needs some care: while the switch-off of a large number of cells (i.e., a small value of x) leads to a large energy saving per unit time, the traffic profile might be such that this is possible only for short periods. In this case, switching off a smaller number of cells for longer periods might yield larger energy savings.

In this paper we show how to optimize this energy saving, first assuming that any fraction of cells can be turned off, and then accounting for the constraints resulting from the cell layout.

II. OPTIMAL ENERGY SAVING SCHEMES

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 a typical daily traffic pattern. The cellular access network is dimensioned so that at peak traffic a given QoS constraint is met. If the QoS constraint is met under traffic $f(0)$, clearly it is also met for smaller values of traffic intensity, and thus during the whole day. We assume that in the considered area all cells have identical traffic patterns.

Consider a power-off scheme S such that, during the low traffic period (called *night zone*), a fraction $x < 1$ of the cells is active, while the remaining fraction, $1-x$, of the cells is off. In the night zone, the x *on* cells have to sustain, in addition to their own traffic, the traffic that in normal conditions is taken care of by the $1 - x$ *off* cells; their traffic becomes:

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

i.e., they receive $1/x$ times their own traffic. Thus, in order to always satisfy the QoS constraint, scheme S can be applied

whenever the traffic is so low that $f^{(S)}(t)$ is still below 1, that is the peak hour traffic. Starting from the peak hour, with decreasing $f(t)$, the earliest time instant τ in which S can be applied is defined by:

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

so that:

$$\tau = f^{-1}(x) \quad (3)$$

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

Let us now focus on a day/night traffic pattern that is symmetric around $T/2$, i.e., such that $f(\tau) = f(T - \tau)$ with $\tau \in [0, T/2]$. The duration of the *night zone* is $T - 2\tau$. Denote by W the power consumption of a cell. The average energy consumed per cell in a day under scheme S is equal to:

$$
\begin{aligned}
C(\tau) &= 2\left[W\tau + Wf(\tau)\left(\frac{T}{2} - \tau\right)\right] \\
&= 2W\left[\tau + f(\tau)\left(\frac{T}{2} - \tau\right)\right] \quad (4)
\end{aligned}
$$

since for a period 2τ 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:

$$Net_{Saving} = 1 - \frac{C(\tau)}{WT} \quad (5)$$

In order to find the optimal power-off scheme, we compute the value $\tau_m \in [0, T/2]$ such that the energy consumption $C(\tau_m)$ is minimum. We assume that $f(t)$ is monotonically decreasing in the interval $[0, T/2]$. The value of τ_m can be obtained from the derivative of $C(\tau)$:

$$\frac{dC(\tau)}{d\tau} = 2W\left[1 + f'(\tau)\left(\frac{T}{2} - \tau\right) - f(\tau)\right] \quad (6)$$

letting

$$2W\left[1 + f'(\tau_m)\left(\frac{T}{2} - \tau_m\right) - f(\tau_m)\right] = 0 \quad (7)$$

$$1 - f(\tau_m) = -f'(\tau_m)\left(\frac{T}{2} - \tau_m\right) \quad (8)$$

or, equivalently,

$$f(\tau_m) - f'(\tau_m)\left(\frac{T}{2} - \tau_m\right) - 1 = 0 \quad (9)$$

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 time τ, and $Wf(\tau)$ for time $\left(\frac{T}{2} - \tau\right)$. In order to minimize energy consumption, we need the rectangular white area in the figure to be the largest possible. The rectangular area has edges of length $1 - f(\tau)$ and $T/2 - \tau$, so that the area is:

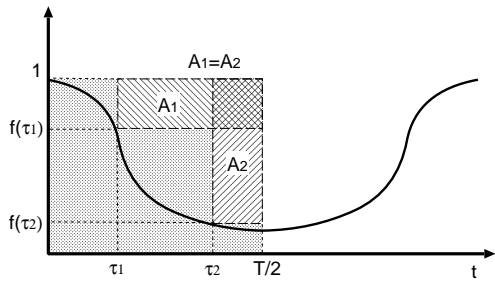$$A = \left(\frac{T}{2} - \tau\right)(1 - f(\tau)) \quad (10)$$

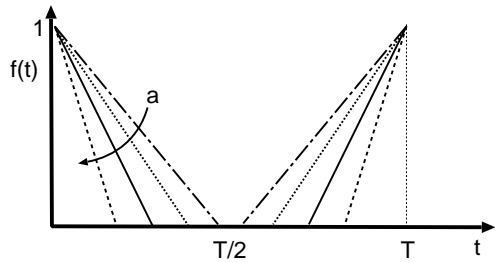Fig. 2.   Two switch-off schemes achieving to the same energy saving

Fig. 3.   Trapezoidal traffic pattern

with maximum defined by the equation:

$$\frac{dA}{d\tau} = f(\tau) - f'(\tau)\left(\frac{T}{2} - \tau\right) - 1 = 0 \qquad (11)$$

which is the same as (8). Notice that, by considering area A, it is easy to see that there may exist different switch-off schemes corresponding to the same energy saving; for example, in Fig. 2, two schemes S_1 and S_2 corresponding to switch-off times τ_1 and τ_2 lead to the same energy saving, since $A_1 = A_2$. Moreover, there may be different points that are minimum of the function $C(\tau)$.

Consider now the case of a non-symmetric traffic pattern $f(t)$, as in the bottom part Fig. 1. Let τ_1 and τ_2 be the two extremes of the night zone for scheme S, with $f(\tau_1) = f(\tau_2)$, and let $g(\tau_1)$ express the difference $\tau_2 - \tau_1$. The average energy consumed per cell in a day under scheme S is equal to:

$$
\begin{aligned}
C(\tau_1) &= W\left[T - (\tau_2 - \tau_1) + f(\tau)(\tau_2 - \tau_1)\right] \\
&= W\left[T - g(\tau_1) + f(\tau_1)g(\tau_1)\right]
\end{aligned}
\qquad (12)
$$

The derivative is:

$$\frac{dC(\tau_1)}{d\tau_1} = W\left[-g'(\tau_1) + f'(\tau_1)g(\tau_1) + f(\tau_1)g'(\tau_1)\right] \qquad (13)$$

and

$$W\left[-g'(\tau_1) + f'(\tau_1)g(\tau_1) + f(\tau_1)g'(\tau_1)\right] = 0 \qquad (14)$$

again identifies the value of τ_1 that yields the maximum white area in the figure.

A. A trapezoidal traffic pattern

As a special simple example of daily traffic pattern we consider the family of symmetric trapezoidal curves plotted

in Fig. 3, with maximum equal to 1 at the peak hour, and different slopes, defined by the angular coefficient a:

$$f(t) = \begin{cases} 1 - at & 0 \le t < 1/a \\ 0 & 1/a \le t \le T/2 \end{cases} \qquad (15)$$

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

Applying the result in (8), the minimum energy consumption can be achieved for

$$a\tau_m = a\left(\frac{T}{2} - \tau_m\right) \qquad (16)$$

so that:

$$\tau_m = \begin{cases} T/4 & \text{if } T/4 < 1/a \\ 1/a & \text{otherwise} \end{cases} \qquad (17)$$

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

The resulting total network saving with respect to an always-on scheme is:

$$Net_{Saving} = \frac{aT}{8} \qquad (18)$$

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

III. ENERGY SAVING IN REAL NETWORKS

While in the previous section we derived the optimal energy saving considering the shape of function $f(t)$ only, in real cases it is not possible to switch off *any* fraction of cells, since the access network geometry and the actual site positioning allow only a few specific values for x, the fraction of cells that remain on during the night zone.

Some typical cellular network configurations are the following:

- Hexagonal cells with omnidirectional antennas: the base transceiver station (BTS) is located at the center of the cell. During the night zone, the cells around one cell that remains on are switched off. We consider two possibilities: in the first case, the on cell is in charge of the traffic of the six neighboring off cells, so that 6 cells are switched off out of 7; in the second case, the on cell covers only half of each neighboring cell, while the rest is covered by another on cell, so that 3 out of 4 cells are switched off. These two cases are sketched in the left part of Fig. 4.
- Crossroads cells with omnidirectional antennas: similar to the previous case, the BTS is at the center of the cell, but the geometry of the access network is such that each cell has 4 neighboring cells, partially overlapping; this configuration is typical of streets in a urban scenario. During the night zone, 4 out of 5 cells are switched off, as depicted in the right part of Fig. 4.
- Hexagonal cells with tri-sectorial antennas: the BTS is at a vertex of the cell, during night the cell expands so as to cover the equivalent of 4 or 9 cells. This scheme results
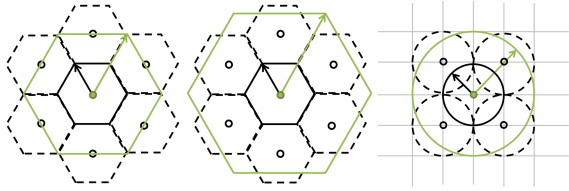
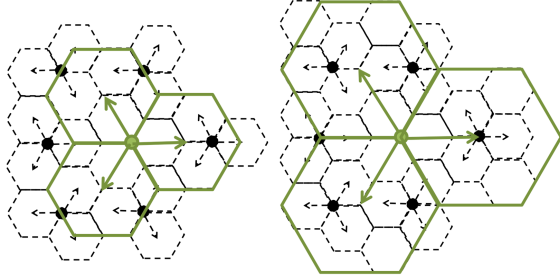Fig. 4. Hexagonal and crossroad configurations

Fig. 5. Hexagonal three-sectorial configuration 3 cells switched off out of 4 (left) and 8 out of 9 (right)

in 3 cells being switched off out of 4 or 8 out of 9, as sketched in Fig. 5.

- Manhattan layout: cells form a grid structure; this case is typical of streets in a urban scenario. Many switch-off schemes are possible, depending on whether the cell is extended along a line or in an omnidirectional fashion, creating square-shaped cells. For the linear case, we consider the schemes represented in top part of Fig. 6 (1 out of 2 cells and 2 out of 3 cells are switched off); for the squared case, as represented in bottom part of the same figure, we consider schemes leading to 3 out of 4 and 8 out of 9 switched off cells.

We consider for these cases two daily traffic patterns: the symmetric trapezoidal traffic pattern introduced in the previous section, and an asymmetric traffic pattern derived from measurements over a real network.

A. Trapezoidal traffic pattern

Fig. 7 shows the network saving versus the angular coefficient a for the case of trapezoidal traffic pattern and for the different network configurations presented above. When the angular coefficient is small, the most convenient power-off schemes are those with small values of x, such as 1/2 or 2/3, since they correspond to solutions close to the optimal $T/4$. On the contrary, when the slope a is large, large fractions x are preferable.

B. Measured traffic pattern

We now consider the case of a traffic pattern derived from real data collected in the network of an Italian broadband service provider, whose network traffic we can access in a portion of our city. The network is wired, so the set of accessed services and the kind of generated traffic may be different from those of a cellular network; still, these data can be considered representative of real user activity. The daily traffic pattern is reported in Fig. 8. As usual, traffic is normalized to the peak;
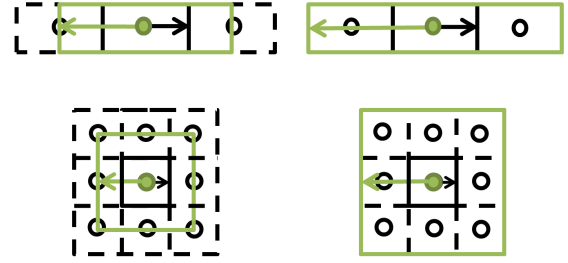

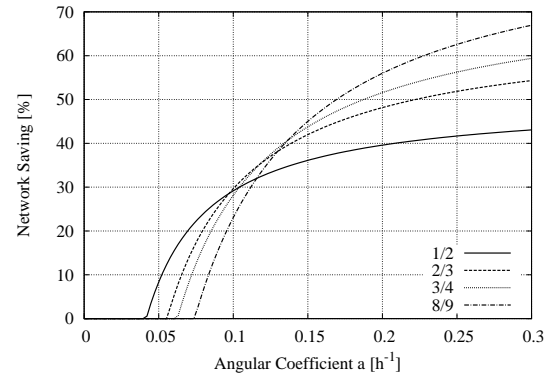Fig. 6. Manhattan configurations: linear (top) and squared (bottom).

Fig. 7. Network saving versus angular coefficient

the peak hour is 11a.m., which corresponds to $t = 0$ in our notation.

Given this traffic function $f(t)$, the saving that can be achieved in the different cases of site positioning and geometry are reported in Table I. Notice that $NodeB_{Saving}$ is, for the Node-B's that can be switched off, the daily fraction of time spent off; while Net_{Saving} is the energy saving achieved in the whole access network as in (5). The table clearly indicates that, among the considered options, the best solution is not to switch off the largest possible number of cells; on the contrary, it is important to trade off between the duration of the night zone and the number of off cells: in our case, the best performing scheme corresponds to 4 cells switched off out of 5.

The curves shown in Fig. 9 represent, for time τ, the network saving that can be achieved by starting the night zone in τ, and by switching off the corresponding fraction $f(\tau)$ of cells. The cases of both the trapezoidal and the measured daily traffic patterns are considered in the figure. The markers correspond to the feasible schemes. Interestingly, with the measured traffic pattern, any scheme achieves at least 25% saving. Moreover, there is not that much difference in the actual saving the schemes may achieve; this means that, under that traffic function, regardless of the specific configuration of the actual network in operation (site positioning and geometry), there is room for considerable energy saving by adopting some simple power-off scheme.

Finally, assume now that we want to make a general comparison of two configurations, without considering a specific traffic profile. Take, for example, the hexagonal configurations,
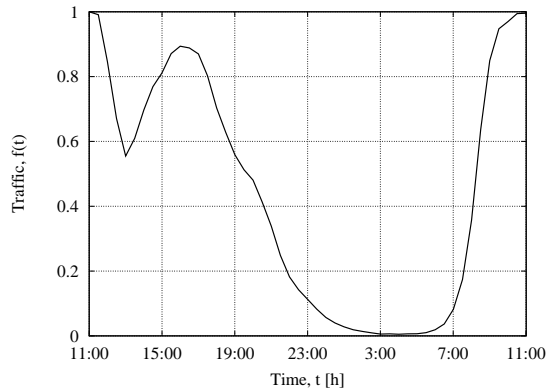
Fig. 8. Traffic intensity: a real profile

TABLE I
RESULTS FOR DIFFERENT CONFIGURATIONS SCENARIOS

Switch-off scheme	$NodeB_{Saving}$ [%]	Net_{Saving} [%]
(1,2) Manhattan/linear	52.3	26.16
(2,3) Manhattan/linear	45.4	30.29
(3,4) Hexagonal/squared	42.5	31.92
(4,5) Crossroad	35.62	32.35
(6,7) Hexagonal	36.8	31.60
(8,9) Hexagonal/squared	33.9	30.13

corresponding to 3 cells off out of 4, or 8 out of 9. Let τ_1 and τ_2 be the instants in which the two schemes become possible; clearly, $\tau_2 > \tau_1$, and the actual value of these instants depends on the specific traffic profile. As depicted in Fig. 10, based on the distance between τ_1 and τ_2, and their relative value with respect to T, it is possible to find regions in which the first scheme is more convenient than the second, and vice-versa. The first scheme is preferable when the slope of the traffic profile, $f(t)$, is low, so that τ_2 is quite distant from τ_1, and the time to wait before the second scheme becomes possible is long. On the contrary, when the slope of $f(t)$ is large, it is convenient to wait for the second scheme to become feasible. Similar plots can be obtained for the comparison of other pairs of configurations.

IV. CONCLUSIONS

We have investigated the possibility of reducing the energy consumption of the access portion of a cellular network by reducing the number of active cells during the periods in which they are under-utilized because traffic is low.

Introducing some simplifying assumption about network traffic and technology, the most important of which are: i) traffic is uniform across cells, and ii) when a cell is switched off, coverage can be filled by its neighbors, we have first derived expressions for the optimal energy saving as a function of the daily traffic pattern, disregarding the cell layout. Then, we have also considered several regular cellular topologies, proving that energy savings of the order of 25-30% are possible. These figures provide a huge incentive for cellular network operators to devise approaches to dynamically manage the resources in
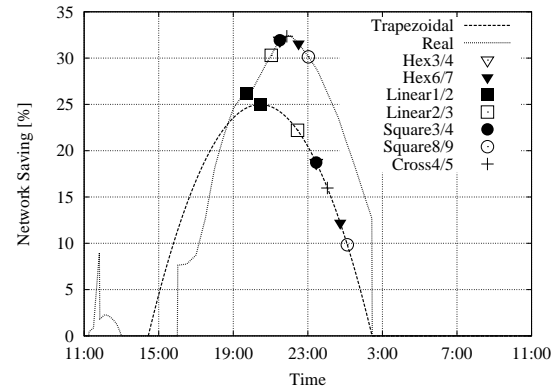

Fig. 9. Network saving functions versus time with different traffic profiles
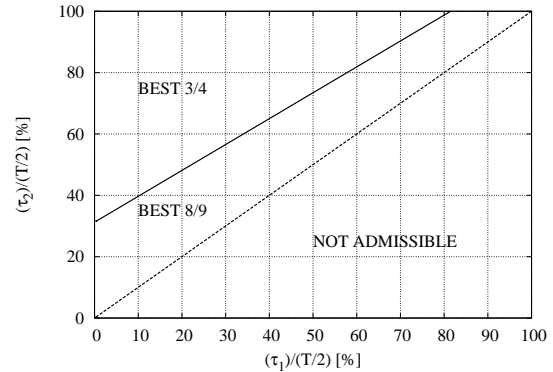

Fig. 10. Comparison between 3/4 and 8/9 configurations

their networks, so as to obtain very large energy savings.

Several extensions and refinements of the results presented in this paper are possible. First of all, a more precise consideration of the effects of cell switch-off on coverage is needed, accounting for technological aspects, such as cell breathing and antenna tilting. Second, the effect of different traffic patterns in neighboring cells should be investigated. Third, and possibly most interesting, while in this paper we only considered a binary choice, where cells can be either on or off, the possibility of choosing among several efficiency (and energy) levels for cells, could be studied.

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