

# Switch-Off Transients in Cellular Access Networks with Sleep Modes

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**Abstract**—The introduction of sleep modes in the operations of base stations is today considered one of the most promising approaches to reduce the energy consumption of cellular access networks. Several papers have considered this option, assuming that the switch-on and switch-off transients are of negligible duration. In this paper we study the switch-off transients for one cell, investigating the amount of time necessary to implement the switch-off, while allowing terminals to handover to a new BS without overloading the signaling channels, and we show that the switch-off durations have a marginal impact on the energy savings achievable with the sleep mode scheme.

## I. INTRODUCTION

Several facts indicate that sleep modes (also called low-power modes) are presently considered one of the most promising approaches for the reduction of the energy consumption of networks and networking equipment. First of all, the very recently adopted Energy Efficient Ethernet (EEE) standard (IEEE 802.3az) [1] is based on the definition of low-power operational modes when the link and the NIC (Network Interface Card) are idle. In addition, several recent papers investigated the possibility of dynamically reducing the number of active elements in wired and wireless networks in periods of low traffic, without compromising the quality of service (QoS) experienced by end users. In the case of wireless access networks, sleep modes were proposed for both WLANs [2] and cellular networks. The latter case is particularly relevant, since the vast majority (80 to 90%) of the energy that is consumed in a cellular network is due to its wireless access segment. For this reason, several research groups tackled this aspect, considering different options, ranging from the switch-off of some Base Stations (BSs) within one network [3], [4], [5], to the reduction of the number of active transmitters [6], to the switch-off of a whole network, when coverage is provided by other technologies of the same operator [7], or when several operators offer coverage in the same service area [8], by allowing customers to roam from the network that switches off to one that remains on.

Almost invariably, in the previous publications which considered the introduction of sleep modes in wireless access networks, the achievable energy savings were computed assuming that the switch-off of BSs can be instantaneous. Obviously, this is not the case; working equipment requires some time to be turned off, and these time intervals can have a significant effect on the energy and performance characteristics of the

sleep mode (consider for example the impact of the switch-off and switch-on periods in EEE [9]). In addition, in the case of cellular access, turning off very rapidly a BS implies disconnecting the users which are connected to it.

In this paper we study the switch-off transients for one cell in a wireless cellular access network, with reference to the UMTS technology. Our approach can be sketched by considering the case of only two BSs ( $BS_1$  and  $BS_2$ ) that cover a service area where several users are present with their mobile terminals (MTs). Some of the terminals receive the signal from both BSs, but some others only receive the signal from the BS which is closest, due to the received signal and interference relative strengths. If we switch off  $BS_1$  very rapidly, the terminals which are connected to  $BS_2$  are not affected; those that are connected to  $BS_1$  are dropped, including the MTs that receive the signal of both BSs and might handover to  $BS_2$ . On the contrary, if we progressively reduce the power at which  $BS_1$  transmits, the number of terminals that receive only  $BS_2$  increases, as well as the number of terminals that receive the signals of both BSs, so that we can progressively induce handovers from  $BS_1$  to  $BS_2$ . We analyze these switch-off transients for different BS layouts (we start with the 2-BS case, and then consider linear and hexagonal layouts, ending with a realistic situation referring to downtown Bologna), investigating the amount of time necessary to implement the switch-off while allowing terminals to handover to a new BS without overloading the signaling channels. We finally discuss the impact of switch-off durations on the energy savings achievable with the sleep mode scheme. We focus on the downlink direction, since this is much more energy hungry than the uplink, and can thus have a larger impact on energy saving. In addition, while the BS switch-off is an innovative feature, the user terminals handovers from a BS to another are common, due to mobility.

Our results indicate that switch-off durations can be fairly short, of the order of 1 minute at most, thus not reducing significantly the energy savings of sleep mode approaches in cellular access networks.

## II. PROBLEM DEFINITION

We consider a BS  $X$ , whose switch-off decision is taken at a given instant  $t_0$ , based on a predetermined sleep mode scheme. For simplicity we assume  $t_0 = 0$ . We assume that the sleep mode scheme has been engineered so that the switch-off

of  $X$  does not degrade QoS, meaning that: the neighboring BSs have enough capacity to carry all the traffic, including the traffic due to MTs in the coverage area of  $X$ ; and, when  $X$  is off, the neighboring BSs of  $X$  can still provide full coverage. We need to derive a *power reduction profile* for  $X$  that jointly guarantees three conditions: i) the MTs connected to  $X$  can handover to neighboring cells, and only very few (if any) are dropped, ii) the handover overload for neighboring cells is kept small, i.e., the number of simultaneous handovers never exceeds the maximum defined by the operator, iii) the switch-off duration is as short as possible, compatibly with the requirements of the network and the users. The power reduction profile is defined by the function  $P_X(t)$  that specifies the transmitted power of BS  $X$  at time  $t$ . For the profile we use a step function such that from time  $t_i$  to time  $t_{i+1}$  the transmission power of  $X$  is constant and equal to  $P_X(t_i)$ , with  $i = 0, 1, \dots, M$ ,  $P_X(t_0) > P_X(t_1) > \dots > P_X(t_M) = 0$  and  $t_0 < t_1 < \dots < t_M$ . The typical normal transmission level of  $X$  is  $P_X(t_0)$ . At time  $t_M$ , BS  $X$  is switched off. The duration of the switch-off procedure is thus given by  $t_M$ , since  $t_0 = 0$ .

To derive the power reduction profile we proceed as follows. We first specify the power levels, i.e., the values  $P_X(t_i)$ , for  $i = 0, 1, \dots, M$ . In this paper, with no loss of generality, we assume that the power emitted by the BS being switched off is progressively halved, i.e.,  $P_X(t_1) = P_X(t_0)/2$ ,  $P_X(t_2) = P_X(t_1)/2$ , and so on, up to the minimum transmission power  $P_X(t_{M-1})$ ; at the following step the BS is switched off,  $P_X(t_M) = 0$ . At the beginning of the switch-off period,  $X$  is transmitting at its typical value,  $P_X(t_0)$ . We compute in this situation the number of MTs connected to  $X$  that also hear other BSs. Assuming that at time  $t_0$  these MTs start to handover out of  $X$ , because  $X$  signals that it is about to switch off, we compute the duration of the time interval it takes to complete the handovers. Time  $t_1$  is set equal to this duration. At  $t_1$ ,  $X$  decreases its transmission power to  $P_X(t_1) = P_X(t_0)/2$ . Given that the power decreased, some MTs that are connected to  $X$  start also hearing other BSs and can handover out of  $X$ . We again derive how much time it takes for these handovers, and this duration defines the amount  $t_2 - t_1$  that  $X$  needs to spend at transmission power level  $P_X(t_1)$ . We iterate this process up to the minimum power level  $P_X(t_{M-1})$ . The possible remaining MTs, that cannot hear other BSs but  $X$  at power level  $P_X(t_{M-1})$ , are dropped<sup>1</sup> when, at  $t_M$ ,  $X$  is completely switched off.

Thus, the derivation of the power reduction profile requires the computation of the number of MTs connected to  $X$  that can (or cannot) hear other BSs. Given the transmission power  $P_X(t_i)$ , we thus define two kinds of regions around  $X$ : in the *dropping area*, that is the closest region around  $X$ , the MTs cannot be connected to other BSs and cannot handover to other BSs, so that on-going calls are dropped if the BS is switched off from this power level; in the *common areas* the MTs can be connected to other BSs besides  $X$ , meaning that

<sup>1</sup>Although dropping users is clearly not desirable, the risk of a handover failure is inherent in the design of cellular systems.

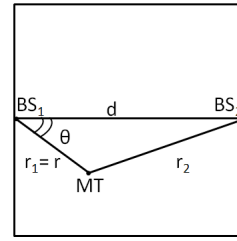


Fig. 1. The case of two BSs.

they can handover out of  $X$ .

The areas are thus defined by the mechanism of the soft handover, as implemented in UMTS. The handover decision is based mainly on the measurement of the SIR on the Primary Common Pilot Channel (P-CPICH), that typically uses 5-10% of the total BS power [10] (in what follows we will always use 10%). A MT can connect to a BS if the Signal-to-Interference Ratio (SIR) of the pilot channel is greater than a given threshold, typically set to  $\delta = -20dB$ . Consider the BS  $X$  transmitting at time  $t$  the pilot at power  $P_{p,X}(t)$ , and consider a MT at distance  $r$  from  $X$  and distance  $r_i$  from BS  $i$ , consider also that BS  $i$  transmits at power  $P_i(t)$ . The MT perceives the pilot SIR of  $X$  as:

$$SIR_{p,X}(t) = \frac{\frac{P_{p,X}(t)}{L(r)}}{\sum_{i=1}^B \frac{P_i(t)}{L(r_i)} + N_0 + I_{ACI}} \quad (1)$$

where  $L(r)$  is the path loss, and the denominator represents the total received interference, that is given by the received power from other BSs (we consider that  $B$  base stations, including  $X$ , give non-negligible interference contribution), the thermal noise density  $N_0$  and the adjacent channel interference  $I_{ACI}$  (see [10] for details).<sup>2</sup>

The MT can be connected to  $X$  if  $SIR_{p,X}(t) \geq \delta$ . The MT is in the dropping area of  $X$  if  $X$  is the only BS for which the SIR is larger than  $\delta$ .

In this work, we first consider the simple case of two adjacent cells; we then extend our analysis to more general cases: the linear and the hexagonal cell layout. Finally, we analyze a case study with a real cell deployment in the city center of Bologna.

### III. TWO CELLS

#### A. Dropping areas

Consider the two BSs case sketched in Fig. 1. Let  $d$  be the distance between  $BS_1$  and  $BS_2$ , and let  $A_1^{(d)}(t)$  and  $A_2^{(d)}(t)$  be the dropping area of  $BS_1$  and  $BS_2$  at time  $t$ . The common area is denoted by  $A^{(c)}(t)$ . Consider a MT located at distance  $r_1$  from  $BS_1$  and  $r_2$  from  $BS_2$ . The pilot SIR received by the MT from  $BS_i$ , with  $i = 1, 2$ , is given by

$$SIR_{p,i}(t) = \frac{\frac{P_{p,i}(t)}{L(r_i)}}{\frac{P_1(t)}{L(r_1)} + \frac{P_2(t)}{L(r_2)} + N_0 + I_{ACI}} \quad (2)$$

<sup>2</sup>Note that we consider omnidirectional antennas. The impact of directional and beamforming antennas can be taken into account by adding an antenna gain factor to (1)

where  $P_1(t)$  and  $P_2(t)$  are the total transmission power of  $BS_1$  and  $BS_2$ , respectively, and  $P_{p,i}(t)$  is the pilot transmitted power of  $BS_i$ .

To simplify notation, we let  $r_1 = r$ . Adopting the same assumptions of [11], we model the path loss as  $L(r) = Kr^\alpha$ , where  $K$  is a constant and  $\alpha$  is between 3 and 4 (if not otherwise stated, we use  $\alpha = 3$  in the following). Moving to polar coordinates with respect to  $BS_1$ , so that the MT position is given by  $(r, \theta)$ ,  $r_2$  becomes  $r_2 = \sqrt{r^2 - 2dr \cos(\theta) + d^2}$ . Thus, (2) is transformed into:

$$\begin{aligned} SIR_{p,1}(t) &= \frac{\frac{P_{p,1}(t)}{Kr^\alpha}}{\frac{P_1(t)}{Kr^\alpha} + \frac{P_2(t)}{K(r^2 - 2dr \cos(\theta) + d^2)^{\alpha/2}} + N_0 + I_{ACI}} \\ SIR_{p,2}(t) &= \frac{\frac{P_{p,2}(t)}{K(r^2 - 2dr \cos(\theta) + d^2)^{\alpha/2}}}{\frac{P_1(t)}{Kr^\alpha} + \frac{P_2(t)}{K(r^2 - 2dr \cos(\theta) + d^2)^{\alpha/2}} + N_0 + I_{ACI}} \end{aligned} \quad (3)$$

The dropping and common areas are defined by:

$$\begin{cases} SIR_{p,1}(t) \geq \delta \wedge SIR_{p,2}(t) < \delta & BS_1 \text{ dropping area} \\ SIR_{p,1}(t) < \delta \wedge SIR_{p,2}(t) \geq \delta & BS_2 \text{ dropping area} \\ SIR_{p,1}(t) \geq \delta \wedge SIR_{p,2}(t) \geq \delta & \text{common area} \end{cases} \quad (4)$$

By assuming that the interference in the dropping area is dominated by the transmitted power of the BSs, and neglecting the contribution of  $N_0$  and  $I_{ACI}$  (we verified for the scenarios that are reported in the numerical results sections, that correspond to urban scenarios with high BSs density, that the impact of these assumptions is negligible), the border of  $A_1^{(d)}(t)$  is defined by the equation  $SIR_{p,2}(t) = \delta$  with  $N_0$  and  $I_{ACI}$  equal to 0, that becomes,

$$\left[ \left( \frac{b}{a} \right)^2 - 1 \right] r^2 + 2dr \cos(\theta) - d^2 = 0 \quad (5)$$

with

$$b = \sqrt[3]{P_{p,2}(t) - \delta P_2(t)}, \quad a = \sqrt[3]{\delta P_1(t)} \quad (6)$$

In Cartesian coordinates, (5) corresponds to a circle of center  $\hat{C}$  and radius  $\hat{r}$ :

$$\hat{C} = \left( \frac{-d}{\left( \frac{b}{a} \right)^2 - 1}, 0 \right), \quad \hat{r} = \frac{db/a}{\left( \frac{b}{a} \right)^2 - 1} \quad (7)$$

The dropping area  $A_1^{(d)}(t)$  can be computed as the area under the chord passing through  $BS_1$ , as shown in Fig. 2. Using standard trigonometry, we can write,

$$A_1^{(d)}(t) = \frac{\pi}{2} \hat{r}^2 + \hat{r}^2 \arcsin \frac{h - \hat{r}}{\hat{r}} + (h - \hat{r}) \sqrt{2h\hat{r} - h^2} \quad (8)$$

with

$$h = \hat{r} - \frac{d}{\left( \frac{b}{a} \right)^2 - 1} \quad (9)$$

Similarly, we can compute the dropping area  $A_2^{(d)}(t)$  of  $BS_2$ , i.e., the zone in which the MTs hear  $BS_2$  but not  $BS_1$ .  $A_2^{(d)}(t)$  corresponds to part of a circle with center and radius defined as in (7), with

$$b = \sqrt[3]{\delta P_2(t)}, \quad a = \sqrt[3]{P_{p,1}(t) - \delta P_1(t)} \quad (10)$$

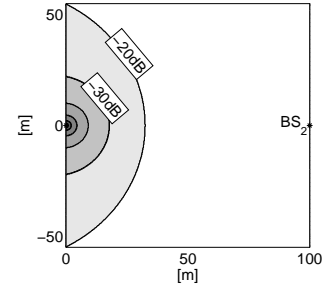


Fig. 2. Two BSs:  $SIR_{p,2}$  levels at -20, -30, -40, -50 dB, for two BSs with the same power.

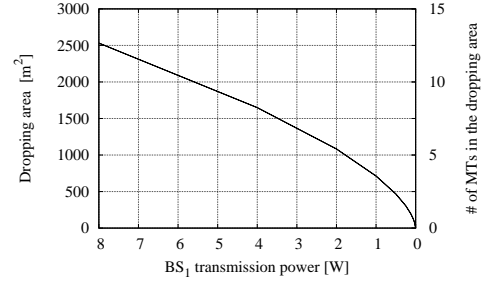


Fig. 3. Two BSs: dropping area size, and average number of users in the dropping area (left and right scales, respectively) versus the transmission power of  $BS_1$ .

and the area is given by (8), with

$$h = \hat{r} + \frac{d}{\left( \frac{b}{a} \right)^2 - 1} + d \quad (11)$$

The common area is given by the complement of  $A_1^{(d)}(t)$  and  $A_2^{(d)}(t)$  over the total considered service area. Assuming that the 2 BSs are 100 m apart, and that the service area is a rectangle of  $100 \times 110$  m, as shown in Fig. 2, we report in the same figure a few  $SIR_{p,2}$  level curves computed when the two BSs transmit at the same power. As expected, the  $SIR_{p,2}$  levels are below the threshold  $\delta = -20$  dB in the dropping area, that is shaded. All MTs in this area cannot handover to  $BS_2$ , and the abrupt switch-off of  $BS_1$ , if not performed with a gradual power decrease, would imply that their calls are dropped.

To derive the power reduction profile, we assume that  $BS_1$  is the cell to be switched off, and that its transmission power levels are halved at each step, from 8 W to  $1/32$  W, before going to zero. For each power level, we compute the dropping area, whose size in  $m^2$  is reported in Fig. 3 as a function of the transmission power.

### B. Switch-off duration

To derive the time instants  $t_i$  of the power reduction profile, we need to compute the durations of the time intervals required for the MTs to handover out of  $BS_1$ , that is switching off. Assume that the MTs are uniformly distributed in the service area, and that their density is  $\rho$ .

At the beginning of the switch-off procedure, the MTs that are in the common area and are connected to  $BS_1$  must

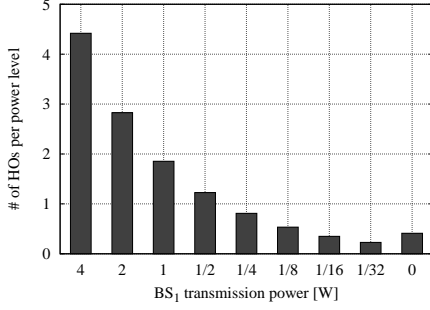


Fig. 4. Two BSs: average number of handovers for each power level  $P_1(t_i)$ ,  $i > 0$ .  $N_h(t_0) = 14.8$ .

handover to  $BS_2$ . Assuming that the MTs are connected to any one of the two BSs with the same probability, the average number of handovers to be performed at the beginning of the switch-off is given by  $N_h(t_0) = A^{(c)}(t_0)\rho/2$ .

Let  $H$  be the maximum number of handovers that can occur simultaneously toward  $BS_2$  (due to signaling channel limits), and let  $T_H$  be the time interval required to complete one handover procedure. The average time interval needed to move all the  $N_h(t_0)$  MTs from  $BS_1$  to  $BS_2$ , considering that  $t_0 = 0$ , is given by:

$$t_1 = \lceil N_h(t_0)/H \rceil \cdot T_H \quad (12)$$

Typically, the percentage of handovers in a cell can involve around 30% of the active MTs, but the actual number depends on many factors; we therefore let  $H$  span over a quite large interval, setting  $H$  equal to 2, 10 or 20.

At  $t_1$ , once all MTs in the common area connected to  $BS_1$  are moved to  $BS_2$ , the power of  $BS_1$  is decreased from  $P_1(t_0)$  to  $P_1(t_1) = P_1(t_0)/2$  and some MTs connected to  $BS_1$  start receiving the pilot channel also from  $BS_2$ . The average number of these MTs, denoted by  $N_h(t_1)$ , is:

$$N_h(t_1) = \rho \left( A_1^{(d)}(t_0) - A_1^{(d)}(t_1) \right) \quad (13)$$

where  $A_1^{(d)}(t_i)$  is the dropping area with power level  $P(t_i)$ . The average duration of the time interval required to handover these MTs to  $BS_2$  is:

$$t_2 - t_1 = \lceil N_h(t_1)/H \rceil \cdot T_H + T_I \quad (14)$$

where  $T_I$  is the time interval a MT takes to identify  $BS_2$ ; indeed, identification is needed before starting a handover. The identification of a new cell is fast if the carrier frequency is the same as for the old cell. A longer time interval is required if the carrier frequency changes, but we do not consider this case. Typical durations for the identification time and the handover time are respectively  $T_I = 0.8$  s and  $T_H = 0.5$  s, as reported in [12]. By iterating the procedure above we get:

$$t_{i+1} = t_i + \lceil N_h(t_i)/H \rceil \cdot T_H + T_I \quad (15)$$

$$N_h(t_i) = \rho \left( A_1^{(d)}(t_{i-1}) - A_1^{(d)}(t_i) \right) \quad (16)$$

where  $N_h(t_i)$  gives, as before, the number of MTs that start hearing  $BS_2$  as soon as  $BS_1$  decreases its power to

TABLE I  
TWO-CELL CASE: AVERAGE SWITCH-OFF DURATIONS AND NO. OF HO

$H$	$t_1$ [s]	$t_M - t_1$ [s]	$t_M$ [s]
2	4	13.2	17.2
10	1	11.7	12.7
20	0.5	11.7	12.2
No. of handovers	14.8	12.7	27.5

$P_1(t_i)$ . After the completion of the handovers at power level  $P_1(t_{M-1})$ ,  $BS_1$  can be finally switched off. The total average switch-off duration is then:

$$t_M = \lceil N_h(t_0)/H \rceil \cdot T_H + \sum_{i=1}^{M-1} (\lceil N_h(t_i)/H \rceil \cdot T_H + T_I) \quad (17)$$

The size of the dropping area at power level  $P(t_{M-1})$  allows the evaluation of the average number of MTs that are dropped when  $BS_1$  is finally switched off,

$$D = \rho A_1^{(d)}(t_{M-1}) \quad (18)$$

where  $A_1^{(d)}(t_{M-1})$  is the dropping area of  $BS_1$  at the minimum power level,  $P_1(t_{M-1})$ .

Fig. 4 reports, for a user density  $\rho = 5 \cdot 10^{-3}$  1/m<sup>2</sup>, the average number of handovers that must be performed at each power level  $P_1(t_i)$ ,  $i > 0$ . The average number of handovers to be performed at  $P_1(t_0)$  is 14.8, as reported in Table I. The last bar, corresponding to  $P_M = 0$  ( $BS_1$  is off), represents the average number of MTs that are dropped when  $BS_1$  is finally switched off. For the aforementioned parameter values of  $T_I$  and  $T_H$ , the average durations to perform the handovers are reported in Table I; in particular, the table reports the average duration  $t_1$  needed to perform all the handovers from the common area at the beginning of the switch-off procedure, the average duration  $t_M - t_1$  necessary to handover the MTs while the power of  $BS_1$  decreases, and the average total switch-off duration,  $t_M$ . The last row of the table indicates the average number of handovers to perform during time intervals  $t_1$ ,  $t_M - t_1$ , and  $t_M$ . Observe that the procedure allows to drop less than 0.5 users on average (instead of the 27.5 that would have been dropped on average with an uncontrolled and abrupt switch-off of  $BS_1$ ) at the cost of an average additional delay between 12 and 18 s. Considering that in an energy-efficient design of the access network a BS is typically switched off for hours, this additional delay of few seconds is negligible.

#### IV. LINEAR AND HEXAGONAL LAYOUTS

In this section, we extend the analysis of the two-cell case to two regular cell layouts: a linear and a hexagonal layout.

For the linear cell deployment, the cell to be switched off is the central one in a row of  $B = 3, 5$  or  $7$  cells, in a rectangular service area of size  $(B+1)d \times 2d$ . In all the analyzed examples, the BSs are at a distance  $d = 100$  m, the user density is  $\rho = 5 \cdot 10^{-3}$  1/m<sup>2</sup>, and the typical transmission power is  $P_i(t_0) = 8$  W.

Fig. 5 reports the dropping area for the three considered linear cases (3, 5, and 7 cells, with label 'Lin'). The slight difference between the curves proves that the interference

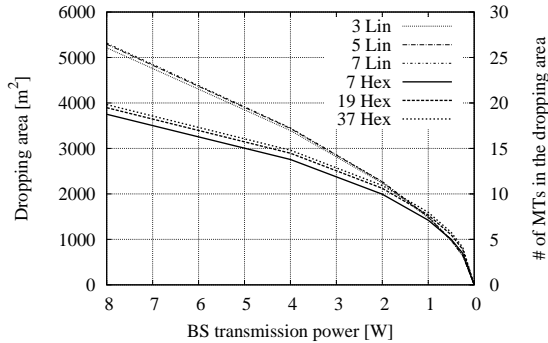


Fig. 5. Linear and Hexagonal layouts: dropping area and average number of MTs in the dropping area versus the BS transmission power.

TABLE II

LINEAR LAYOUT: AVERAGE SWITCH-OFF DURATIONS AND NO. OF HO

$H$	$t_1$ [s]	$t_M - t_1$ [s]	$t_M$ [s]
2	30	15.7	45.7
10	6	11.7	17.7
20	3	11.7	14.7
No. of handovers	119.8	26.1	145.8

contribution on the central cell is mainly given by the two adjacent cells. For the three-cell case, Table II reports the average time intervals required for the switch-off procedure and the average numbers of handovers that must be performed. The BS switch-off average durations are again very small, always smaller than 1 minute. In this case the switch-off procedure allows to drop less than 1 user on average instead of the 145.8 that would have been dropped on average with an uncontrolled and abrupt switch-off.

For the hexagonal layout case, we study the switch-off of a central BS in a regular hexagonal layout composed of 7, 19, or 37 cells, corresponding to the central cell with  $i = 1, 2,$  or  $3$  rings of neighbors. The service area is a square that includes all the cells, and has a side  $2(i+1)d$ . In all the analyzed examples, the distance between BSs is  $d = 100$  m, the user density is, as before,  $\rho = 5 \cdot 10^{-3}$   $1/m^2$ , and the typical transmission power is  $P_i(t_0) = 8$  W. Fig. 6 shows the interference map of the BSs at the beginning of the procedure, when all the BSs have the same transmission power. The different gray levels indicate how many BSs a MT can hear, and the black markers indicate the BSs positions. The common area is now given by the region in which the MTs can hear the central BS and at least another BS. We assume that if a MT in the common area can hear  $g$  BSs, it is connected to the central BS, the one which is switching off, with probability  $1/g$ .

Fig. 5 reports the size of the dropping areas for the three cases (label 'Hex'); again, the small differences between the curves is due to the fact that the neighboring cells give the largest contribution to interference. For the 7-cell case, the average switch-off durations and numbers of handovers are summarized in Tab. III. The average BS switch-off durations are very small also in this case, always less than half a minute. In this case the switch-off procedure allows to drop about 1 user on average instead of the about 52 that would have been dropped on average with an abrupt switch-off.

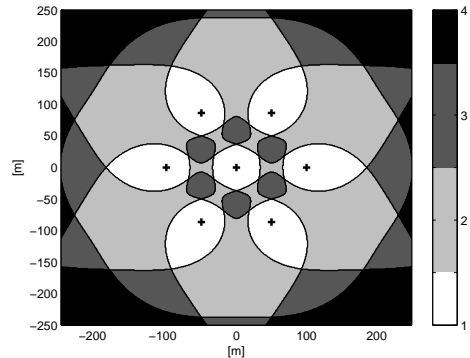


Fig. 6. Hexagonal layout: BSs interference areas.

TABLE III

HEXAGONAL LAYOUT: AVERAGE SWITCH-OFF DURATIONS AND NO. OF HO

$H$	$t_1$ [s]	$t_M - t_1$ [s]	$t_M$ [s]
2	8.5	14.2	22.7
10	2	11.7	13.7
20	1	11.7	12.7
No. of handovers	33.4	18.8	52.2

## V. A REAL CELL LAYOUT

In this section, we analyze a case study with real BS deployment. We consider a zone in the city center of Bologna, in Italy, with seven *Vodafone* BSs, whose positions are specified in [13] and are indicated in Fig. 7 by the black markers. Consider to switch off the BS with coordinates (227, 90), and assume the service area is the square depicted in the figure. At the beginning of the procedure, when all the BSs transmit at the same power, the interference map is the one reported in Fig. 7, in which, as before, different gray levels indicate the number of BSs that can be heard.

Using the same values of transmission power as before, and for a user density  $\rho = 10^{-3}$   $1/m^2$  (the lower user density w.r.t. the previous cases reflects the lower BS density in the service area), the average switch-off durations and numbers of handovers are reported in Table IV. The power decrease profile is detailed in Fig. 8. The average switch-off duration is always less than half a minute, a negligible amount with respect to the typical periods for which a BS is in sleep mode in low traffic conditions. In this case the switch-off procedure allows the cells to drop about 0.1 users on average instead of the about 67 that would have been dropped with an abrupt switch-off.

Finally, to assess the impact of the propagation model parameters, we compute the size of the dropping area versus the transmission power of the BS that switches off with different propagation models. In particular, we consider the previous model with different values of the path loss exponent  $\alpha$ , as well as the Walfisch-Ikegami model [14]. The results are reported in Fig. 9: the labels 'LOS' and 'NLOS' refer to the Line-of-Sight and No-Line-of-Sight versions of the Walfisch-Ikegami model. In the worst case (the LOS case), the average switch-off duration is equal to 29.7 s, with 0.05 MTs dropped at the end of the procedure on average, versus the 75.5 that

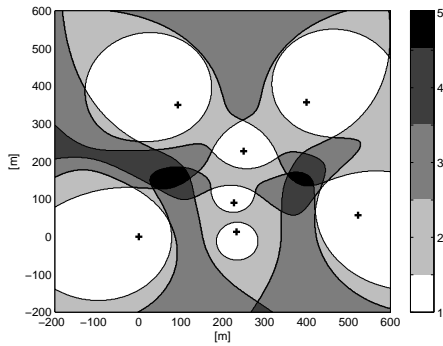


Fig. 7. Real layout: BSs interference areas.

TABLE IV  
REAL LAYOUT: AVERAGE SWITCH-OFF DURATIONS AND NO. OF HO

$H$	$t_1$ [s]	$t_M - t_1$ [s]	$t_M$ [s]
2	15.5	12.2	27.7
10	3.5	11.7	15.2
20	2	11.7	13.7
No. of handovers	61.4	5.7	67.1

would have been dropped with no graceful power decrease. Observe that while the propagation model parameters change the numerical results, the shape of the curves remains the same. This means that an operator can expect to derive a power decrease profile similar to those previously computed, even using more accurate propagation models, and the average switch-off durations are expected to be of the same order of those previously derived, i.e., only a few tens of seconds.

## VI. CONCLUSIONS

In this paper we investigated the transients for the switch-off of BSs in cellular access networks with different layouts, ranging from a very simple 2-cell case, to regular structures, to a real case. For all these BS layouts, we studied the switch-off transients for one cell, investigating the average amount of time necessary to implement the switch-off, while allowing terminals to handover from the BS being switched off to a new BS, without overloading the signaling channels. We computed results using a simple but widely accepted propagation model, and parameters which are considered typical for BSs of today.

The average switch-off durations which result from our analysis are fairly short, of the order of 1 minute at most. If we compare these durations with the durations of the intervals for which a BS can be continuously off, which is estimated in the order of hours by several authors, we can conclude that switch-off transients do not reduce significantly the energy savings of sleep mode approaches. On the contrary, these very short durations of BS switch-offs indicate that sleep modes could be pushed even further than present proposals, switching off BSs also for short periods of reduced load, of the order of quarters of an hour. Of course, such aggressive switch-off schemes must be coupled with effective switch-on schemes, which can quickly react to traffic load increases. Our future work in this field will be oriented toward these options.

Finally, more sophisticated and realistic physical models will be considered.

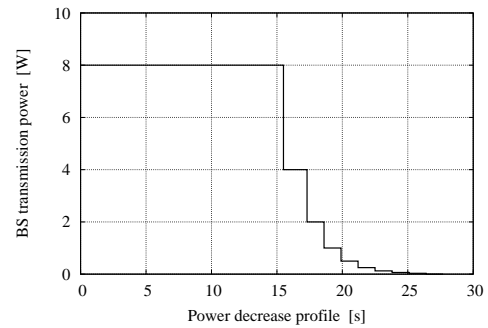


Fig. 8. Real layout: power decrease profile, with  $H = 2$ .

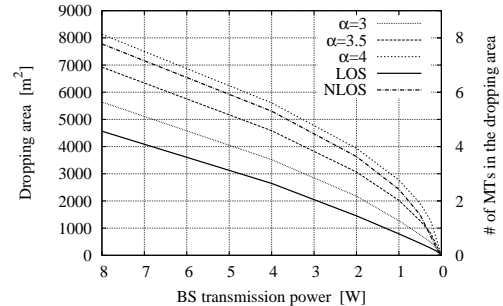


Fig. 9. Real layout: dropping area and average number of MTs in the dropping area for different propagation models.

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## REFERENCES

- [1] IEEE P802.3az Energy Efficient Ethernet Task Force, 2010. URL: <http://grouper.ieee.org/groups/x%802/3/az>.
- [2] A. Jardosh, K. Papagiannaki, E. Belding, K. Almeroth, G. Iannaccone, and B. Vinnakota, *Green WLANs: On-Demand WLAN Infrastructure*, Mobile Networks and Applications (MONET), special issue on Recent Advances in WLANs, April 2009.
- [3] 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.
- [4] 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.
- [5] E Oh, B. Krishnamachari, *Energy Savings through Dynamic Base Station Switching in Cellular Wireless Access Networks*, IEEE GLOBECOM, Miami, USA, December 2010.
- [6] L.i Saker, S. E. Elayoubi, *Sleep mode implementation issues in green base stations*, IEEE PIMRC, Istanbul, Turkey, September 2010.
- [7] D. Tipper, A. Rezgui, P. Krishnamurthy, P. Pacharintanakul, *Dimming Cellular Networks*, IEEE GLOBECOM, Miami, USA, Dec. 2010.
- [8] M. Ajmone Marsan, M. Meo, *Energy Efficient Management of two Cellular Access Networks*, ACM SIGMETRICS Performance Evaluation Review, Special Issue on the 2009 GreenMetrics Workshop, Vol. 37, No. 4 (March 2010), pp. 69 - 73.
- [9] P. Reviriego, J. Hernandez, D. Larrabeiti, and J. Maestro, *Performance Evaluation of Energy Efficient Ethernet*, IEEE Communications Letters, Vol. 13, No. 9, pp. 1-3, September 2009.
- [10] J. Laiho, A. Wacker, and T. Novosad, *Radio Network Planning and Optimisation for UMTS*, John Wiley & Sons, 2002.
- [11] J.-M. Kelif, M. Coupechoux, *Cell Breathing, Sectorization and Densification in Cellular Networks*, WiOpt 2009, Seoul, Korea, June 2009.
- [12] H. Holma, A. Toskala, *WCDMA for UMTS*, John Wiley & Sons, 2004.
- [13] <http://www.arpa.emr.it/cem/webcem/bologna/index.asp>.
- [14] *Cost 231 Final Report*, <http://www.lx.it.pt/cost231/>.