The Impact of Sleep Modes on the Lifetime of Cellular Networks

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***Abstract*—Sustainable networking is becoming a paradigm for cellular operators. In this work, we study the interplay between sleep modes and cellular network failure rates. In particular, we have developed a new model to compute the Base Station (BS) lifetime given the hardware (HW) and sleep mode parameters. The BS model is then extended on the entire network to compute the network lifetime. Our findings show that, under certain conditions, sleep modes may increase the cellular network lifetime. These results are confirmed also adopting a realistic scenario and a sleep mode algorithm.**

I. INTRODUCTION

Energy-efficient networking has been deeply investigated in the last years, starting from the seminal works of [1] and [2]. Focusing on cellular networks, previous work in the literature have investigated the potential of adopting energy-efficient policies for cellular networks (see [3] for a comprehensive overview). In this context, BS sleep mode is a promising approach to reduce energy consumption. Just to mention few examples, the problem has been addressed considering: the energy-efficient management with sleep modes [4], [5], the time needed to wilt and blossom the BS [6], and the joint planning and management [7], [8].

All these works have proven the efficiency and efficacy of BS sleep modes. However, a natural question arises: is sleep mode beneficial for the lifetime of the BS? The problem has not been investigated in the literature, and this paper is a step to answer the question. A first consideration is that the lifetime of the BS is related to the frequency at which failures occur. Failures are particularly critical events for network operators, since they lead to dropped calls and eventually to the lack of coverage in different zones of the network. Additionally, BSs failures introduce also monetary costs, due to the replacement of HW components and the time needed to repair the BS. In this context, operators are particular worried by the introduction of sleep modes, claiming that BSs are not designed to be powered off, and sleep modes may even increase the failure rate due to the variation of temperature introduced on the HW components.

In this work, we focus on the evaluation of sleep modes in terms of lifetime for the cellular network. In particular, we have a new model to compute the lifetime of the single BS. Then, we have extended the model in order to consider the impact on the entire network. Our solution is able to evaluate the impact of sleep modes on the cellular network lifetime, and to provide some insights of this approach on the operator network.

The problem of studying the interplay between sleep modes and device lifetime has been raised in our previous work [9]. Differently from [9], in this work we go one step further by: i) defining the BS lifetime model, ii) introducing a methodology to compute the lifetime of the entire cellular network, iii) evaluating the model, iv) considering a realistic scenario and an energy-aware algorithm to extend the model findings. Additionally, the problem of evaluating the device lifetime in backbone networks is investigated in [10] and [11]. In this work instead we focus our attention on cellular networks, since they are considered to be one of the most power-hungry networks in the ICT sector [12].

The rest of the paper is organized as follows. In Sec. II we present the BS lifetime model. Sec. III extends the model to the entire cellular network. Results obtained from our model and from a realistic case study are presented in Sec. IV. Finally, Sec. V concludes our work.

II. MODELING THE BS LIFETIME

We first consider the model for evaluating the impact of lifetime on the single BS. We define the lifetime D_i of BS i:

$$D_i = \frac{1}{\gamma_i} \text{ [h]} \tag{1}$$

where γ_i is the inverse of the Mean Time To Failure (MTTF), i.e., the failure rate.

When a sleep mode state is applied to a BS, most of its components are put in a low power state. This triggers a temperature variation on the components themselves which impacts the lifetime of the BS. The following subsections are therefore devoted to the definition of the critical parameters that change the temperature of the device, and therefore the failure rate.

A. Impact of Low Power Mode

The failure rate of semiconductor and electronics circuits is decreased when the operating temperature is reduced. The Arrhenius law [13] is a first order model which describes this behaviour. In particular, it can be modeled with the following parameters:

$$\gamma^{\mathcal{T}} = \gamma^0 e^{-\frac{E_a}{\mathcal{K}\mathcal{T}}} \text{ [1/h]} \tag{2}$$

where γ^0 is the failure rate estimated assuming infinite temperature, E_a is the activation energy, $\mathcal{K}$ is the Boltzmann constant, $\mathcal{T}$ is the temperature of the device and $\gamma^{\mathcal{T}}$ is the predicted failure rate for the generic device. Although the Arrhenius law predicts a failure rate decrease with the decrease of temperature, measurements on real devices have shown that this model is a first order approximation, and more accurate models tailored to specific types of devices have been proposed in the literature (see for example [14]).

In our work, we consider the Acceleration Factor (AF) metric [15] to measure the increase/decrease of the failure with respect to a reference temperature:

$$AF^{\mathcal{T}_1} = \frac{\gamma^{\mathcal{T}_1}}{\gamma^{\mathcal{T}_r}} = e^{-\frac{E_a}{\mathcal{K}}\left(\frac{1}{\mathcal{T}_1} - \frac{1}{\mathcal{T}_r}\right)} \tag{3}$$

In particular, $\gamma^{\mathcal{T}_1}$ is the failure rate at current temperature while $\gamma^{\mathcal{T}_r}$ is the failure rate at reference temperature.

B. Impact of Power Switching

A BS that is in low power needs to be powered on again when traffic increases. Similarly, the BS can be put in sleep mode when traffic decreases again. The variation of power on the BS triggers a variation of temperature, which is not instantaneous. This variation has an effect on the failure rate, which is called thermal cycling. In particular, the more frequently the temperature is varied the higher will be also the failure rate. A first-order model describing this effect is the Coffin-Mason equation [15], [16]:

$$N^f = C_0(\Delta_{\mathcal{T}} - \Delta_{\mathcal{T}_0})^{-q} \tag{4}$$

where $\Delta_{\mathcal{T}}$ is the temperature variation, $\Delta_{\mathcal{T}_0}$ is the maximum admissible temperature variation without a variation in the failure rate, C_0 is a constant material dependent, q is the Coffin-Mason exponent, and N^f the number of cycles to failure. The total failure rate is then defined as:

$$\gamma^{\Delta_{\mathcal{T}}} = \frac{f^{TC}}{N^f} \text{ [1/h]} \tag{5}$$

where f^{TC} is the frequency of thermal cycling and $\gamma^{\Delta_{\mathcal{T}}}$ is the estimated failure rate. Thus, we can see that the variation of temperature on the BS triggers the thermal cycling effect.

C. The BS failure rate model

In our model, we consider both the decrease of the failure rate from Eq. (2) and the increase of the failure rate from Eq. (5). In particular, we first define γ_j^{on} as the failure rate of BS j in normal operation, i.e., at full power. Moreover, we define γ_j^{off} and γ_j^{tr} as the failure rates of BS j in low power and during the switching transient, respectively. In our case, γ_j^{tr} is defined as $\gamma_j^{tr} = f_j^{tr}/2N_j^f$, where f_j^{tr} is the frequency of power switching and the factor 2 takes into account that the cycle is composed of two transitions (from full power to low power and from low power to full power again).

The total failure rate of BS j is then defined as:

$$\gamma_j = \left[(1-\tau_j^{off})\gamma_j^{on} + \tau_j^{off}\gamma_j^{off}\right] + \gamma_j^{tr} \text{ [1/h]} \tag{6}$$

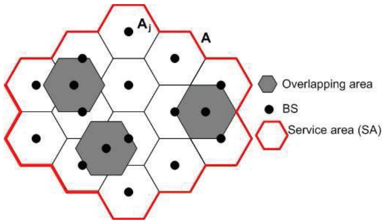

Fig. 1. An example of the considered scenario.

In particular, the model is composed by two terms: on the left we consider the impact of low power mode (weighed by τ_j^{off}, which is the normalized amount of time spent by the device in low power mode), while on the right we take into account the power switching effect. By assuming that the failure rate due to the different effects are statistically independent from each other [17], we compute the total failure rate as the sum of the two aforementioned terms.

Similarly to the Arrhenius law case, also here we define an acceleration ratio AF. In particular, we define the acceleration factor AF_j of BS j as the ratio between the failure rate computed from Eq. (6) and the failure rate at full power:

$$AF_j = \frac{\gamma_j}{\gamma_j^{on}} = 1 - (1 - AF_j^{off})\tau_j^{off} + \chi_j f_j^{tr} \tag{7}$$

$$AF_j^{off} = \frac{\gamma_j^{off}}{\gamma_j^{on}} \tag{8}$$

$$\chi_j = \frac{1}{2\gamma_j^{on} N_j^f} \tag{9}$$

In (7), the acceleration factor AF_j of BS j is governed by technological parameters (namely γ_j^{on}, γ_j^{off} and χ_j) which depends on the HW characteristics, and τ_j^{off} and f_{jk}^{tr} which are governed by the realization of low power modes on the devices. Additionally, the term χ_j can be defined as the number of hours per cycle. Intuitively, this term acts as a weight for the frequency of transitions f_j^{tr}. The higher is χ_j, the higher will be also AF_j, resulting in a decrease of the BS lifetime. Moreover, we can observe that τ_j^{off} and f_j^{tr} are determined by the specific sleep mode functionality implemented in the BS.

III. CELLULAR MODEL

Let us consider a network composed of M BSs. The average network lifetime can be defined as

$$E = \frac{\sum_j^M D_j}{M} \text{ [h]} \tag{10}$$

Moreover, we define E^{on} as the network lifetime at full power, i.e. $\sum_j^M \frac{1}{\gamma_j^{on} M}$. Then, the network acceleration factor AF is:

$$AF = \frac{E}{E^{on}} \tag{11}$$

More in depth, total surface of the service area (SA) which must be covered with cellular signal equals to A (km^2). Inside SA set $S = \{1, \cdots, M\}$ of macro BSs sites containing BSs of specific cellular technology (2G, 3G or 4G) can be allocated. In the analyses, cellular network with BSs of one technology, all transmitting in the same frequency band (e.g. 3G BSs transmitting at 2100 MHz band) will be considered. For simplicity, each active j-th macro BS transmits continuously at the same Tx power and covers hexagonal coverage area A_j. Hence, homogeneous network containing identical BS in terms of HW configuration will be considered. An example of the considered scenario is reported in Fig. 1.

Let us assume that the minimum number of macro BSs necessary for ensuring full coverage of the SA is known and equal to M_{min}, what results in $A = A_j M_{min}$. Small overlapping among M_{min} of active BSs needed for ensuring seamless handover will be neglected as overlapping among other $M - M_{min}$ BSs. Without loss of generality, chosen assumptions fairly corresponds to the real cellular network implementations. Accordingly, level of the coverage overlapping for the SA can be expressed as:

$$K = \frac{\sum_j^M A_j - \sum_j^{M_{min}} A_j}{\sum_j^{M_{min}} A_j} = \frac{M - M_{min}}{M_{min}} \tag{12}$$

where $K \geq 0$ corresponds to the overlapping coefficient. In the case of $K = 0$, there is no overlapping and for $K = 1, 2, 3, ...$ some parts of the SA are covered with cellular signal from at least two, three, four, etc. macro BSs, respectively.

We assume that when sleep modes are applied, a number of pM macro BSs is put in standby or power saving mode, being $p \in (0, 1)$. In particular, assuming that the pM macro BSs will be turned off as result of energy consumption optimization scheme, the new number of active macro BSs in the network becomes: $M' = M(1 - p)$.

The percentage of BSs p that can be turned off as a result of energy-efficient radio resource management is defined by the coverage and the BS capacity constraints. In particular, we consider the percentage p of turned off macro BSs that jointly satisfies the following conditions:

i) *Coverage constraint* It is assumed that to ensure minimum network coverage, each part of the SA A must be in any moment covered with the cellular signal detected from at least one BS. The following constraint in terms of BSs that can be in standby mode satisfies this criteria:

$$p \leq \frac{M - M_{min}}{M} = 1 - \frac{1}{1 + K} \tag{13}$$

Based on relation Eq. (13), for larger overlapping coefficient, higher percentage of BSs can be switched off in case when radio resource management scheme dedicated to improve network energy-efficiency will be implemented.

ii) *BS capacity constraint* Due to space variation of network traffic, some BSs can be more loaded than the others. In order to prevent overloading of BSs above their maximal capacity C_j, BS capacity constraint must be introduced. Consider an SA with M base stations all having the same number of cells (sectors). Moreover, let us define $R(t)$ as the total traffic that needs to be supported over the service area, which is normalized to 1 for the peak hour. By assuming that the traffic is equally distributed among the BSs, we define the traffic for each BS $F(t)$ as $F(t) = R(t)/M$. Finally, the maximum capacity of j-th BS C_j^{max} is normalized such that $C_j^{max} = 1/M$ and is equal to $F(t)$ of BS during peak hour $t = 0$.

When energy-efficient network management scheme is implemented, during periods of low traffic a percentage p $(p < 1)$ of M BSs will be in low power mode or completely switched off.[1] Hence, $(1 - p)M$ BSs with corresponding cells will be active, and in addition to their own traffic $F(t)$, those BSs must take over traffic that in normal condition is taken care of by the pM sleeping BSs. Thus, total traffic of a single BS during low-power (LP) period can be expressed as:

$$F^{(LP)}(t) = F(t) + \frac{pM}{(1-p)M} F(t) = \frac{F(t)}{(1-p)} = \frac{R(t)}{(1-p)M} \tag{14}$$

In order to satisfy BS capacity constraint, Eq. 14 must be lower than the maximum BS capacity C_j^{max}. Therefore, BS capacity constraint can be expressed as:

$$p \leq 1 - R(t) \tag{15}$$

Eq. (15) computes percentage of BSs that can be switched-off while capacity of each active BSs will not be exceeded. Supposing that traffic $R(t)$ varies over time on a period T, we compute the maximum fraction of BSs $r(t)$ that jointly satisfies Eq. (13)-(15) according to the traffic $R(t)$ at time t, with $t \in (0, T)$.

In the following, we then consider the impact of $r(t)$ in the lifetime model. In particular, we first assume that the same failure rate is applied to all BS in the SA, i.e., $\forall\, j\ \gamma_j^{on} = \gamma^{on}$, $\gamma_j^{off} = \gamma^{off}$, $N_j^f = N^f$. Thus, it holds that $AF_j^{off} = AF^{off}$ and $\chi_j = \chi$. Moreover, we assume that $r(t)$ is a continuous function that can be integrated. We then express the averaged total time in sleep mode as:

$$\frac{\sum_j^M \tau_j^{off}}{M} = \frac{1}{T} \int_0^T r(t)\, \mathrm{d}t \tag{16}$$

Additionally, we denote $\bar{f}^{tr}$ as the average power switching rate in the network, i.e., $\bar{f}^{tr} = \frac{\sum_j^M f_j^{tr}}{M}$. Then, the average AF of the network is:

$$AF = 1 - \frac{1 - AF^{off}}{T} \int_0^T r(t)\, \mathrm{d}t + \chi \bar{f}^{tr} \tag{17}$$

which thus computes the network acceleration factor given the cellular model, the traffic profile, and the HW parameters AF^{off} and χ. Note that when $AF < 1$ sleep modes increase the network lifetime.

If we consider the coverage constraint and we neglect the thermal cycling effect, i.e., $\chi \bar{f}^{tr} = 0$ it is possible to obtain

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[1] In a real network the number of BSs switched off will be the nearest integer to pM.

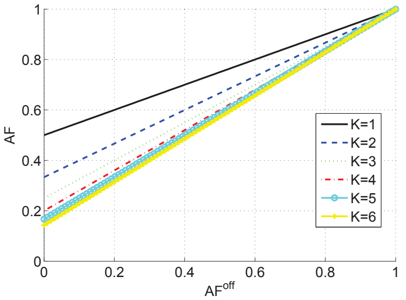

Fig. 2. Lower bound variation of AF vs. AF^{off} and K.

the following lower bound for AF from Eq. 17:

$$AF \geq \frac{1}{1+K} + \left(1 - \frac{1}{1+K}\right) AF^{off} \tag{18}$$

IV. PERFORMANCE EVALUATION

We first evaluate the lifetime of the network considering the proposed model. Then, as a second step, we consider a realistic case study.

Model Results Initially, we compute the maximum lifetime achievable in the network from the lower bound of Eq. 18. Fig. 2 reports the minimum network AF achievable considering the variation of AF^{off} and K. Interestingly, AF decreases with AF^{off}, meaning that, as BSs implement power saving primitives decreasing the single BS failure rate, the network AF promptly decreases. Moreover, we can observe that also the overlapping coefficient K plays an important role, since very overlapped networks (i.e., with high values of K) further increase the network lifetime. This is true especially in urban areas, where BSs are densely placed to meet the user requirements during the day, while during the night many BSs can be switched off since traffic is low while guaranteeing network connectivity.

To give more insight, we consider also the traffic variation over time. In particular, we adopt the traffic profile model of [18]:

$$R(t) = \begin{cases} \frac{(L-1)(1-H)}{L-H}\frac{2t}{T} + 1 & 0 \leq t < \frac{T}{2}\frac{L-H}{1-H} \\ \frac{(L-H)(1-H)}{L-1}(\frac{2t}{T} - 1) + H & \frac{T}{2}\frac{L-H}{1-H} \leq t \leq \frac{T}{2} \end{cases} \tag{19}$$

$L \in (0,1)$ and $H \in (0,1)$ are two parameters governing the width and the depth of the off-peak zone, respectively. From now on, we consider a traffic profile sampled over 200 points, which corresponds to a traffic variation every 7 minutes.

To test the impact of the traffic profile, we first consider $L = 0.5$. Moreover, we consider $\chi = 0$ to better evaluate the impact of AF^{off}. Fig. 3 reports the network lifetime AF versus the variation of H and AF^{off}. By adding the traffic variation, we can see that the obtained AF is higher than the lower bound of Fig. 2. This is due to the fact that the introduction of traffic imposes to switch off less BSs compared to the ideal case. However, we can see that the resulting AF is always lower than 1, meaning that the network lifetime is increased. In particular, we can observe that AF decreases as H is reduced. Intuitively, with low values of H, the depth of the off-peak zone is increased, resulting in a larger number of BSs switched off.

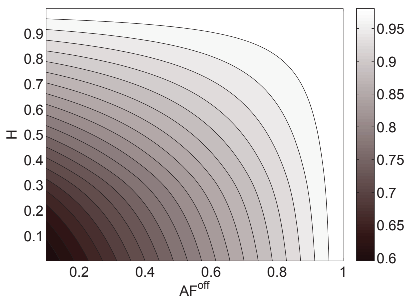

Fig. 3. AF variation vs. AF^{off} and H.

We then introduce the thermal cycling effect by considering also the variation of χ. In particular, by assuming that $r(t)$ is monotone on period T, with maximum at $t = 0$ and $t = T$ and symmetric around $T/2$ we compute the average switching transitions as:

$$\bar{f}^{tr} = \frac{\int_0^T |r'(t)|dt}{T} = \frac{2(r(T/2) - r(0))}{T}. \tag{20}$$

Fig. 4 reports the network AF versus the variation of AF^{off} and χ for different values of L. Additionally, we set $H = 0$ to consider the deepest off peak zone. By considering the thermal cycling effect, we can see that there is clearly a tradeoff between the zone in which AF is lower than 1 (bottom left of the figures) and the region in which $AF > 1$ (top right of the figures). Recall that $AF < 1$ means that the network lifetime is increased compared to the always on solution. The red curve marks the crossover line $AF = 1$. Two considerations hold for the figures: first, for low values of L (right figure), the width of the off-peak is large. Therefore, many BSs can be put in sleep mode for a long time period, resulting in a gain on the network lifetime for $\chi \in (0,10)$ [h/cycle]. On the contrary, when L is reduced, the gain of sleep mode is also reduced, and the crossover line is moved to the left. This means that, as less BSs can be put in sleep mode, the HW parameters introduced in χ tend to assume a predominant role. In this case, sleep mode should be carefully planned in order to avoid the case $AF > 1$.

Real Case-Study In the last part of our work, we consider an energy-aware algorithm and a realistic scenario, both obtained from [19]. Due to the lack of space, we refer the reader to [19] for a comprehensive description. In brief, we consider a scenario with 33 BSs and an SA of 9.2×9.2 km^2. Inside the SA, we assume more than 3000 user terminals (UTs) requesting voice and data services. Moreover, we assume a day-night traffic variation. Over such scenario, we solve the problem of minimizing the number of active BSs while guaranteeing coverage and capacity demand of all UTs which are active in each time period.

Fig. 5 reports AF considering the variation of AF^{off} and χ. In this case, we have first computed τ_j^{off} and f_j^{tr} for each BS. Then, as a second step, we have computed the average

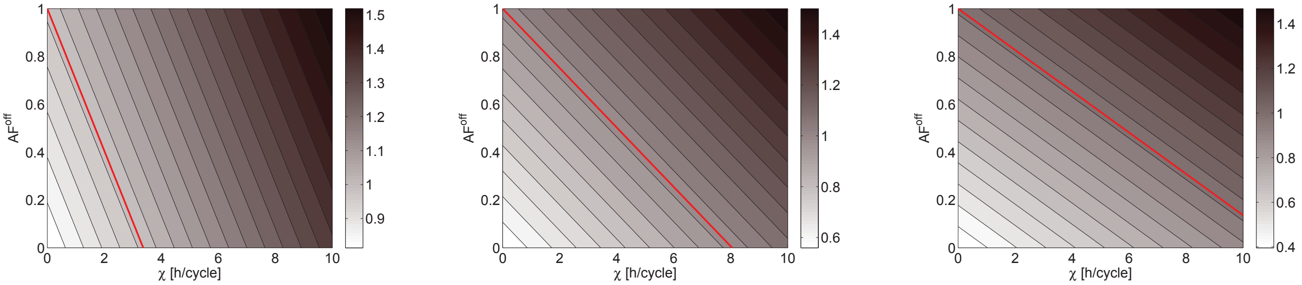

Fig. 4. AF variation vs. AF^{off} and χ. L=0.8 (left), L=0.5 (center), L=0.2 (right)

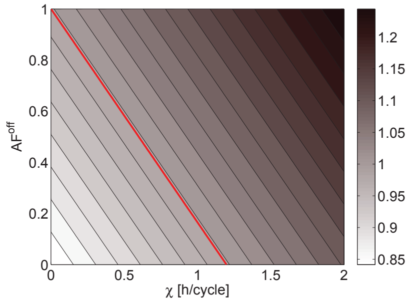

Fig. 5. AF variation vs. AF^{off} and χ for the case-study scenario.

network AF. Interestingly, the region in which sleep modes increases the network lifetime is even reduced compared to the model scenario. This is due to more realistic constraints introduced in the simulation, which prevent to put in sleep mode some of the deployed BSs. Additionally, a BS switched off in one time period may be turned on again in the following time period, thus triggering the thermal cycling effect. Thus, we can conclude that sleep modes should be carefully planned to increase the network lifetime.

V. CONCLUSIONS AND FUTURE WORK

We have developed a new model to predict the lifetime of a cellular network with sleep modes. Our findings show that the lifetime is influenced by the network topology, the traffic variation, and the HW characteristics of the BS. In particular, we have shown that the lifetime can be increased when sleep modes are applied. However, frequent activation/deactivation of BSs may eventually deteriorate the network lifetime, due to the thermal cycling effect. Therefore, we claim that a more comprehensive approach is needed, targeting not only the maximization of energy saving but also the increase of the network lifetime. Additionally, we will evaluate the impact of putting in sleep mode the single HW components rather the entire BS. Moreover, we will introduce the reparation time in our model, as well as considerig the maximum network lifetime increase.

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