

# Is Green Networking Beneficial in Terms of Device Lifetime?

Luca Chiaraviglio<sup>1</sup>, Pawel Wiatr<sup>2</sup>, Paolo Monti<sup>2</sup>, Jiajia Chen<sup>2</sup>, Josip Lorincz<sup>3</sup>,  
Filip Idzikowski<sup>4</sup>, Marco Listanti<sup>1</sup>, Lena Wosinska<sup>2</sup>

<sup>1</sup>DIET Department, University of Rome Sapienza, Rome, Italy, email {luca.chiaraviglio}@uniroma1.it

<sup>2</sup>Optical Networks Lab, KTH Royal Institute of Technology, Kista, Sweden

<sup>3</sup>FESB-Split, University of Split, Split, Croatia

<sup>4</sup>Poznan University of Technology, Poznan, Poland

**Abstract**—This paper analyses the impact that sleep mode (SM)-based green strategies have on the reliability performance of optical and cellular network elements. First, we consider a device in isolation (i.e., not plugged into a network in operation), showing how operational temperature and temperature variations, both introduced by SM, impact its lifetime. We then evaluate, from an operational cost perspective, the impact of these lifetime variations, showing that some devices are critical, i.e., their achievable energy savings might not cover the potential additional repair costs resulting from being put too frequently in SM. Moreover, we present a model for evaluating the impact of SM on the lifetime of a device plugged into a network in operation. The analysis considers two case studies (one based on optical backbone and one on cellular networks) showing that the lifetime of a device is influenced by both the hardware parameters (that depend on the specific design of the device) and the SM parameters (that instead depend on the energy-efficient algorithm used, the network topology, and the traffic variations over time). Our results show that (i) the changes in the operational temperature and the frequency of their variation are two crucial aspects to consider while designing a SM-based green strategy, and (ii) the impact of a certain SM-based strategy on the lifetime of network devices is not homogeneous, i.e., it can vary through the network.

**Index Terms**—Sustainable Networks; Green Networking; Energy-Lifetime Tradeoff; Lifetime Models; Cellular Networks; Optical Networks.

## I. INTRODUCTION

In the past years the energy efficiency of communication networks has been the focus of an extensive research work. Many green approaches have been proposed in the literature in order to reduce the energy consumption of both cellular and fixed networks, at all layers, and in all network segments (i.e., access, metro/aggregation, and core) [2], [3].

One of the most promising approaches to save energy is to put idle network devices in *sleep mode* (SM), a state in which a network element consumes less energy compared to fully operational mode. In the case of backbone optical networks, this means putting into SM transponders, regenerators,

reconfigurable optical add/drop multiplexers (ROADMs), and erbium doped fiber amplifiers (EDFAs). In cellular networks SM can be used, for example, with base stations (BSs), and remote radio units (RRUs). However, the adoption of SM approaches can trigger also other effects, different from energy saving. In particular, SM cycles may vary the operating temperature of a device and, in turn, may affect its lifetime [4].

More in depth, temperature can impact the reliability performance of a device in different ways. For example, the lifetime of a device can be extended, when its operational temperature is reduced [1]. Thus SM-based green techniques could be beneficial. On the other hand, frequent temperature variations may accelerate the occurrence of failures [5] and, in turn, shorten the lifetime of devices. These aspects need to be carefully assessed, because any change in a device reliability performance impacts the network operational cost in terms of extra failure repair expenditures [4]. Therefore, it is important to make sure that the extra repairs caused by the decreased lifetime of some network devices does not exceed the potential savings from using an energy-efficient strategy.

This paper presents a comprehensive study assessing the impact that SM-based green strategies have on the lifetime of network devices. The study considers the main network elements used in cellular and in backbone optical networks. The objective of the study is twofold: (i) identify the devices that may experience the highest impact on the operational cost increase due to a possible reliability performance degradation, and (ii) assess the reliability performance degradation measured in terms of *Acceleration Factor* (*AF*) of the network elements that are set to SM during network operation. This latter aspect is vital to assess the vulnerability of the network as a whole (i.e., defined in terms of how frequently network elements are likely to experience a failure).

Our results indicate that the *AF* of a device is a function of its hardware (HW) characteristics, and of the specific energy efficient strategy that inevitably sets the values of the device SM periods and frequencies. The results of the study also confirm that in order to benefit from an energy-efficient strategy the SM switching frequency has to be kept to a minimum. Finally, when comparing cellular with optical devices, the latter ones seem to be more susceptible to reliability

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performance degradation from the operational cost perspective.

## II. LIFETIME VARIATIONS: PHYSICAL PHENOMENA

When a device goes to SM, its operating temperature may be reduced because a number of its internal components is switched to an off or stand-by mode. There are several models in the literature that can be used to characterize how much temperature variations impact the lifetime of a device. One of them is the Arrhenius law [6] which determines how much the failure rate increases/decreases, if a device is operated at a temperature different from a reference one. According to the Arrhenius law, if the operating temperature of a device is reduced, its failure rate becomes smaller as well. This means that, by considering only the effects of the Arrhenius law, an energy-efficient scheme would have a positive impact on the lifetime of a device, since the operating temperature of a device in SM is typically lower than the one at full power.

However, there are also other physical phenomena that need to be considered, and may negatively impact the lifetime of a device. It is well known that temperature changes may affect differently the expansion of different materials within the same device if they have different coefficients of temperature expansion. In turn, a device may suffer strain and fatigue when temperature conditions change, in particular when this happens in a cyclic way. This phenomenon can be observed for many electronic devices, in particular for solder junctions. The Coffin-Manson model [7], [8] describes the effects of material fatigue caused by cyclic thermal stress and it is used to predict the number of temperature cycles that a component can endure before failing. In particular, the more often a device experiences a temperature variation, the shorter its lifetime might become. This effect occurs when the device passes from full power to SM, and vice-versa. In the remainder of the paper, the lifetime variations of network devices are modeled using the Arrhenius law and the Coffin-Manson model.

## III. ENERGY-EFFICIENCY VERSUS LIFETIME VARIATIONS: AN OPERATIONAL COST PERSPECTIVE

This section presents an assessment from the operational cost perspective of what is the maximum tolerable lifetime decrease when setting to SM the main active devices used in wavelength division multiplexing (WDM) optical backbone networks and in cellular networks.

A lifetime degradation introduces an additional OPERational EXpenditure (OPEX) in terms of failure reparation cost. When green strategies are used in a network, this has to be taken into account in the overall OPEX calculation. It is then important to understand up to which point the savings coming from a green strategy can still compensate the extra costs related to the decreased lifetime of a device. This tradeoff can be measured using the maximum allowable lifetime decrease (in percentage compared to the nominal conditions, i.e., when SM is not applied) so that the reparation costs will not exceed the saving obtained by lowering the energy consumption by a given threshold, i.e., 10%. The maximum allowable lifetime

decrease can be expressed in the following way [5]:

$$MaxLD_{10\%} = \frac{\overbrace{10\% \cdot P_{eq} \cdot C_{kWh}}^{\text{monetary energy saving}}}{\underbrace{10\% \cdot P_{eq} \cdot C_{kWh}}_{\text{monetary energy saving}} + \underbrace{\frac{FR}{10^6} \cdot (MTTR \cdot Pers \cdot C_m + C_{eq})}_{\text{reparation costs}}}, \quad (1)$$

where  $P_{eq}$  [W] represents the power consumption in active mode of the device under exam,  $C_{kWh}$  [USD/kWh] is the electricity cost,  $FR$  represents the device failure rate expressed in FIT [units] (i.e., the failure in time unit which corresponds to one failure per  $10^9$  hours of operation),  $MTTR$  [h] is the mean time to repair the device,  $Pers$  [member] represents the number of reparation crew members necessary to repair the failed device,  $C_m$  [USD/h/member/failure] is the hourly rate of a reparation crew member, and  $C_{eq}$  [USD/failure] is the cost to buy a replacement unit of the device under reparation. For example, assuming that the "monetary energy saving" is 400 USD and that the "reparation costs" are 600 USD, according to Eq. (1), the maximum allowable lifetime decrease will be 40%.

Table I presents the values of the maximum allowable lifetime decrease for a number of backbone WDM optical and cellular network devices, including: linecards, transponders, ROADMs, EDFAs, BSs, and RRUs.<sup>1</sup> In particular, we consider two different scenarios: in the first one the device that fails has to be replaced, while in the second one the device can be repaired without involving substitution. To compute the lifetime decrease, we adopt the parameters reported in the Table, with the exception of the cost of energy  $C_{kWh}$  and the hourly rate of crew members  $C_m$  that are equal to 0.16 USD/kWh [12] and 190 USD/h/member/failure [4], respectively.

The lifetime decrease results presented in Table I show that in the scenario without replacement, the majority of the network equipment (with the exception of EDFAs) are able to sustain a significant degradation of their lifetime without a considerable impact on their operational costs, i.e., the maximum allowable lifetime decrease is greater than 10%. In this case, the achievable energy savings from SM can easily compensate the (possible) extra reparation costs. On the other hand, a different conclusion can be drawn in the case of EDFAs, where the values of maximum allowable lifetime decrease are very small.

On the contrary, when replacement costs are taken into account, all network devices under exam (both optical and cellular) have a maximum allowable lifetime decrease below

<sup>1</sup>The input data come from [5], [9], [10], [11], and from the following sources: Cisco ONS 15454 Multiservice Transport Platform - MSTP (<http://www.cisco.com/c/en/us/products/optical-networking/ons-15454-multiservice-transport-platform-mstp/index.html>), CISCO Price List (<http://www.kernelsoftware.com/products/catalog/cisco.html>), EDFA-R Erbium Doped Fiber Amplifier with Redundant Power Supplies (<http://www.pbnglobal.com/en/products/edfa-r>), Huawei GBSS9.0 DBS3900 Product Description V2.1 (<http://cosconor.fr/GSM/Divers/Equipment/Huawei/DBS3900%20product%20description.pdf>), Huawei eLTE3.1 DBS3900 LTE FDD Product Description ([http://enterprise.huawei.com/ilink/cnenterprise/download/HW\\_275863](http://enterprise.huawei.com/ilink/cnenterprise/download/HW_275863))

TABLE I  
MAXIMUM ALLOWABLE LIFETIME DECREASE ANALYSIS

	Device type	$FR$ [FIT]	$MTTR$ [h]	$Pers.$	$C_{eq}$ [kUSD]	$P_{eq}$ [W]	Maximum allowable lifetime decrease (with replacement)	Maximum allowable lifetime decrease (without replacement)
Optical	Multirate DWDM XPonder Card	2900	2	1	10	50	2.59%	42.10%
	10-Gbps Full-Band Tunable Multirate Transponder Card	4200	2	1	25	35	0.52%	26.00%
	40-Channel Single-Module ROADM	3300	2	1	25	35	0.66%	30.90%
	100-Gbps Service Line Card	8600	2	1	190	130	0.18%	38.90%
	16-port Wavelength Mux/ Demux Flex Spectrum line card	6200	2	1	100	100	0.26%	40.40%
	Enhanced 96-Channel EDFA	7100	6	2	15	40	0.52%	3.80%
	EDFA-R	10000	6	2	10	18	0.23%	1.25%
Cellular	LTE RRU (micro/1 cell)	10000	1.5	1	0.65	50	7.88%	21.92%
	LTE Micro BS	6452	2	1	3.9	100	5.48%	39.49%
	LTE RRU (macro, 1 sector/cell)	10000	4	2	2.6	120	4.45%	11.21%
	Main unit Macro BS (3 sector LTE, 2 transceivers/sector)	6452	3	1	15.6	460	6.59%	66.68%
	Macro BS (3 sector UMTS, 2 transceivers/sector)	10000	5	2	32.5	1700	7.33%	58.87%
	Macro BS (3 sector GSM, 2 transceivers/sector)	20000	6	2	45.5	840	2.74%	37.09%

10%, suggesting that the extra repair cost plays a very crucial role from the operational cost perspective. It can also be noticed that the backbone optical devices show the worst lifetime decrease performance. Therefore, optical devices are more critical than their cellular counterpart and need to be considered more carefully.

#### IV. ACCELERATION FACTOR: FROM THE SINGLE DEVICE TO THE NETWORK PERSPECTIVE

The previous section highlighted how SM may impact the operational cost as a consequence of the potential variations of the component lifetime. The study considered a device in isolation. This section goes one step further by looking at the reliability performance of a device plugged into a network in operation, when energy-efficient approaches are applied. The intuition is that when a device is plugged into a network, some of the parameters affecting the device lifetime (i.e., SM duration, frequency of sleep cycles) cannot be known in advance because they are dependent on the specific green strategy and on the network status (e.g., connectivity, congestion, traffic conditions). In order to understand how green network operations impact the lifetime of all devices in a network, it is necessary to first model the lifetime variations, as presented next.

The considerations made in Sec. II highlighted a clear tradeoff between SM duration (i.e., a positive effect modelled by the Arrhenius law [6]) and its frequency (i.e., a negative effect modeled by Coffin-Manson [7], [8]). More formally, the overall failure rate of an arbitrary device  $i$  in the network can be expressed in the following way:

$$\gamma_i = \underbrace{\left[ (1 - \tau_i^{sleep}) \gamma_i^{on} + \tau_i^{sleep} \gamma_i^{sleep} \right]}_{\text{Impact of SM Duration}} + \underbrace{\frac{f_i^{tr}}{N_i^F}}_{\text{Impact of SM Frequency}} \quad [1/h], \quad (2)$$

where  $\tau_i^{sleep}$  is the amount of time spent by the device in SM (normalized to the time the device is under observation),  $\gamma_i^{on}$  is the failure rate at full power,  $\gamma_i^{sleep}$  is the failure rate when the device is in SM,  $f_i^{tr}$  is the frequency of the SM cycles, and  $N_i^F$  is the number of cycles supported by the devices before a failure occurs. The first term in the equation is

derived using [6]. It is the sum of the failure rates at full power and in SM, respectively, weighted by the amount of time the device is in SM. The second term is taken from [7], [8]. It represents the contribution to the failure rate that is a function of how frequently the device operational state changes. The two terms are then added to compute the overall failure rate of the device, assuming that they are statistically independent and their effects are additive [1].

In order to model the lifetime variations of a device, the concept of *Acceleration Factor* ( $AF$ ) is introduced.  $AF$  is a parameter measuring the mean lifetime decrease/increase w.r.t. the device operating in full power conditions (i.e., when SM is not applied). In particular, an  $AF$  larger than one means that SM has a negative impact on the device lifetime, while if  $AF$  is lower than one the device lifetime benefits from the introduction of SM. More formally, the  $AF$  of device  $i$  can be defined as:

$$AF_i = \frac{\gamma_i}{\gamma_i^{on}} = 1 - \underbrace{(1 - AF_i^{sleep}) \tau_i^{sleep}}_{\text{Lifetime Increase}} + \underbrace{\chi_i f_i^{tr}}_{\text{Lifetime Decrease}}, \quad (3)$$

where  $AF_i^{sleep}$  is the  $AF$  experienced by the device when it is always kept in SM, i.e.,  $AF_i^{sleep} = \frac{\gamma_i^{sleep}}{\gamma_i^{on}}$ , which according to [6] is always lower than 1. Intuitively,  $AF_i^{sleep}$  is the minimum  $AF$  achievable by the device when SM is applied and the impact of temperature variation is not considered. This parameter depends on the technology adopted to implement SM of the device: the lower is  $AF_i^{sleep}$ , the higher will be the gain in terms of reliability performance.  $\chi_i$  is a HW parameter, defined as:  $\chi_i = \frac{1}{\gamma_i^{on} N_i^F}$  [h/cycle], which acts as a weight for the frequency of the SM cycles.

The acceleration factor  $AF_i$  comprises two terms:  $(1 - AF_i^{sleep}) \tau_i^{sleep}$  tends to decrease the value of  $AF_i$  due to the temperature decrease during SM, while  $\chi_i f_i^{tr}$  tends to increase the value of  $AF_i$  due to the temperature changes caused by the SM cycles. Moreover,  $AF_i$  is influenced by two types of parameters: technological (i.e.,  $AF_i^{sleep}$  and  $\chi_i$ ) which are strictly related to the HW used to build the device, and SM-related (i.e.,  $\tau_i^{sleep}$  and  $f_i^{tr}$ ) which instead depend on the green strategy used, and on the conditions of the network

in operation.

Even though the proposed model is a first-order approximation, it is already useful to draw some interesting conclusions. The design of a device plays a crucial role, i.e., devices that are designed to better sustain frequent temperature variations are likely to fail less frequently. In addition, the duration and the frequency of SM strongly impact the lifetime. Intuitively, if SM happens frequently, a device experiences frequent power state transitions between full power and SM and consequently its lifetime will be reduced.

Apart from the effects on a single device, an operator is mostly interested to evaluate the impact of SM on the reliability performance of all the devices deployed in the network. One possibility is to use a metric measuring (per each device type) the average value of  $AF$ , e.g., something similar to the  $\overline{AF}$  metric introduced in [1]. However, as the duration and the frequency of SM periods are not the same for all the devices, it might also be interesting to look into the best case and worst case scenarios in terms of  $AF$  for a set of given devices. The next section presents a detailed case study of these aspects.

## V. ACCELERATION FACTOR EVALUATION: A NETWORK LEVEL CASE STUDY

This section evaluates the  $AF$  of a given set of devices when a SM-based green strategy is applied to a network. Two scenarios are considered: (i) a backbone optical network using an energy-efficient routing strategy where energy is saved by setting EDFAs to SM, and (ii) a cellular scenario where BSs are set to SM when not needed to provide coverage and/or capacity. Details on each scenario are presented next.

**Backbone Optical Network Scenario.** We consider a green Routing strategy called Weighted Power Aware Lightpath Routing (WPA-LR) [13] tested on the COST239 backbone optical network. WPA-LR is able to save energy by encouraging the routing of incoming lightpath requests over already used links, thus maximizing the number of unutilized fiber links, i.e., maximizing the number of EDFAs that can be put in SM. A detailed description of the algorithm and the topology characteristics is available in [1].

Connection requests are bidirectional and their source and destination pairs are uniformly chosen among the network nodes. They arrive according to a Poisson process while their service time is exponentially distributed with an average holding time equal to 6 hours. In order to compute the value of  $AF$  for each EDFA deployed in the network, it is assumed that all of them have the same HW characteristics, while the frequency and the duration of each sleep cycle for each EDFA are collected by simulating the WPA-LR algorithm over the COST239 network. Simulation results are averaged over a series of 10 experiments, with  $10^5$  connection requests in each experiment.

**Cellular Scenario.** We consider an energy-aware algorithm and a realistic cellular deployment scenario, both obtained from [14]. Due to the lack of space, we refer the reader to [14] for a comprehensive description. In brief, we consider a

scenario with 33 Universal Mobile Telecommunication System (UMTS) Macro BSs and a Service Area (SA) of  $9.2 \times 9.2$  km<sup>2</sup>. Inside the SA, we assume more than 3000 User Terminals (UTs) requesting voice and data services. Unless otherwise specified, we assume that the maximum data rate for each user is equal to 384 kbps. Moreover, we assume a day-night traffic variation with a deterministic profile over the 24h. For this scenario we solve the optimization problem aimed at minimizing the number of active BSs while guaranteeing the required coverage and capacity demand for all the UTs which are active in each time period. Similarly to the optical case, we assume the same HW characteristics for all BSs, while we collect the frequency and duration of each SM cycle via simulation.

### A. Sleep Mode Duration and Frequency

We first investigate the duration and frequency of the SM cycles, focusing on the optical scenario. In particular, we vary the traffic load between 10 and 420 Erlang. These values are chosen in order to investigate different conditions where the network blocking probability does not exceed 10%. Figs. 1.(a)-(b) report the normalized time in active state and the on/sleep frequency. In particular, given the duration and the on/sleep frequency for each EDFA, we have computed the minimum, maximum and average duration and the on/sleep frequency values. The bars in the figures indicate the confidence intervals for the average values, assuming 99% of confidence level. The time in active state (reported in Fig. 1.(a)) tends to increase with the load. This is due to the fact that EDFAs need to be on average powered on for a longer time in order to sustain the load increase. For load  $>350$  Erlang nearly all EDFA are on, since in this case all links are used. Focusing then on the maximum values, we can see that for load  $>50$  Erlang, there are already some EDFAs that are always powered on. However, focusing on the minimum values, we can see that until medium load (i.e.,  $<250$  Erlang), there are EDFAs that are powered on for less than 10% of the time. This means that the duration of SM varies depending on the device, and consequently the effect of SM on the device lifetime is not the same for all the EDFAs.

Fig. 1.(b) reports the maximum, average, and minimum EDFAs on/sleep frequency values expressed in cycles per day. Interestingly, the average on/sleep frequency tends to be higher at lower load, due to the fact that WPA-LR only considers power minimization, while the on/sleep frequency is not taken into account. Consequently, solutions reducing power consumption might result in frequent on/sleep cycles. Focusing on the minimum values, we can see that there are EDFAs which seldom change their power state, resulting in frequency almost close to zero (as expected). These EDFAs are either in full power or in SM for most of the time. Finally, we can see that the maximum on/sleep frequency is three times higher than the average for load of 10 Erlang. Thus, similarly to the duration of SM, also the on/sleep frequency varies considerably among the EDFAs in the network.

Fig. 1.(c) reports the normalized time in active state and

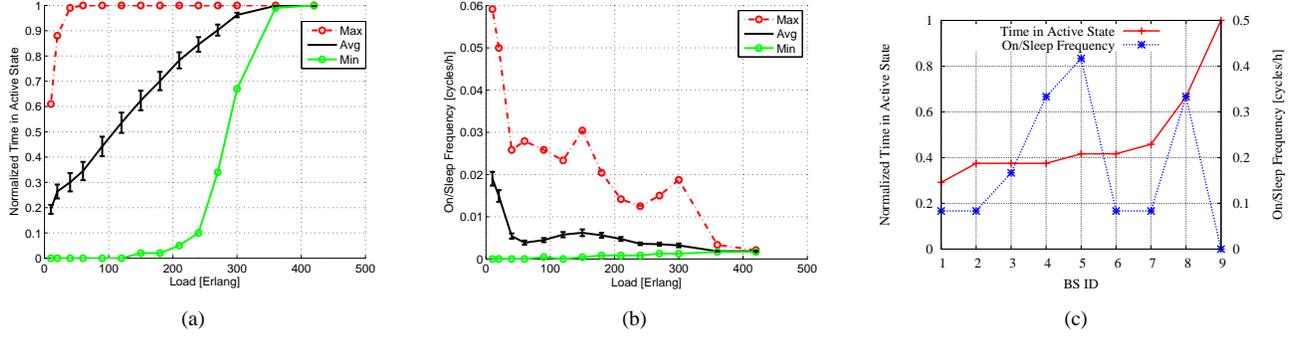


Fig. 1. Maximum (Max), average (Avg), and minimum (Min) normalized time in active state (a) and active/sleep switching frequency (b) for the optical scenario, and (normalized) time in active state and active/sleep switching frequency for each base station experiencing SM cycles in the cellular scenarios (c).

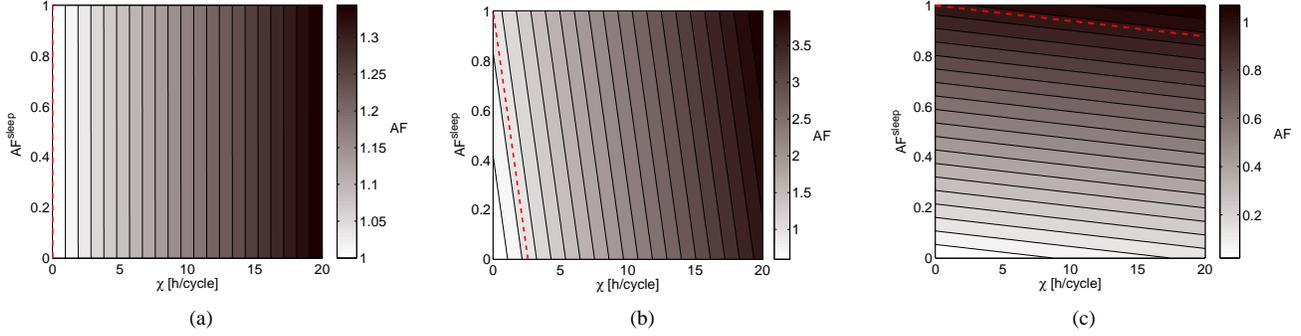


Fig. 2. Acceleration Factor ( $AF$ ) in the optical scenario: worst  $AF$  value (a), average  $AF$  value (b), and best  $AF$  value (c) as a function of  $\chi$  and  $AF^{sleep}$  (Load=150 Erlang).

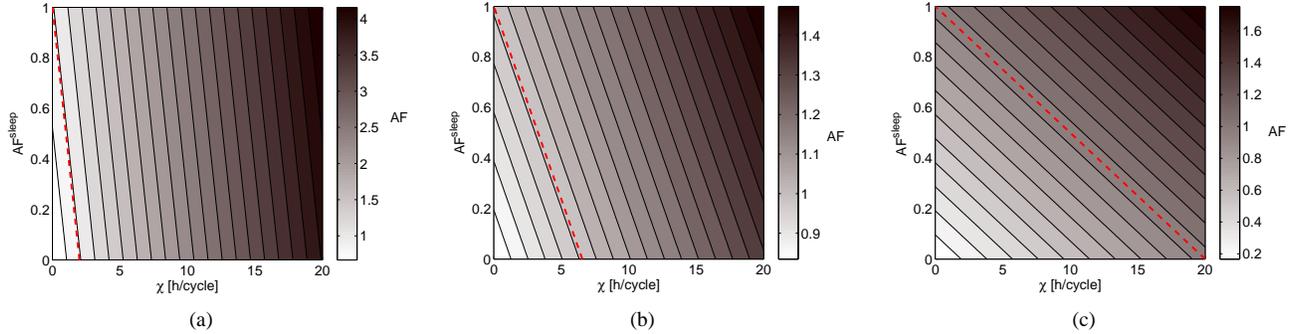


Fig. 3. Acceleration Factor ( $AF$ ) in the cellular scenario: worst  $AF$  value (a), average  $AF$  value (b), and best  $AF$  value (c) as a function of  $\chi$  and  $AF^{sleep}$ .

the on/sleep frequency for the cellular scenario. The figure presents results for each BS having at least one on/sleep cycle per day (we exclude BSs that are always at full power or in SM). Interestingly, also here we can see a variation in the time in active state and on/sleep frequency, suggesting that the impact of SM on the lifetime will not be the same for all BSs.

### B. Acceleration Factor

Since  $AF$  is a function of the HW parameters (i.e.,  $\chi$  and  $AF^{sleep}$ ), we vary them to compute the resulting value of  $AF$  for all the EDFAs in the optical scenario (Fig. 2), and for all the BSs in the cellular scenario (Fig. 3). In doing so

we assumed that all EDFAs or all the BSs, depending on the scenario considered, have the same HW parameters.

Fig. 2.(b) shows the average values of  $AF$  over all the EDFAs in the network, considering a load of 150 Erlang. The red dashed line highlights the level curve  $AF = 1$ . The region on the left of this line represents the zone where on average EDFAs in the network fail less often when compared to the case in which the energy-aware algorithm is not used, i.e.,  $AF < 1$ . On the contrary, the region on the right is the zone where  $AF > 1$ , i.e., EDFAs on average are expected to fail more often when compared to the case in which WPA-LR is not used. From the figure, it can be noticed that the HW parameters play a crucial role in determining the impact

of an energy-efficient strategy in terms of average lifetime decrease/increase. In particular,  $AF^{sleep}$  has always a positive effect on the lifetime, i.e., in SM the operating temperature of an EDFA is lower. On the other hand, the frequency weight becomes the discriminating factor, meaning that EDFAs whose  $\chi$  is very high (in this case higher than 2.7 h/cycle) will experience on average a reduced lifetime.

Besides the average, Fig. 2 reports the worst (a) and the best (c)  $AF$  values. While computing them we did not consider the EDFAs that are either in SM or in full power all the time since they represent trivial cases. In the worst  $AF$  scenario, the curve  $AF = 1$  is very close to the y-axis, meaning that SM will always result in a decrease of the EDFA lifetime. This is due to the fact the EDFA under consideration frequently changes its power state, with very short SM intervals. On the contrary, for the best  $AF$  scenario,  $AF$  is always lower than 1 (for the values of  $\chi$  considered in the figure). This is for example the case of an EDFA that is powered off for a long time (e.g., it is powered on only in the case of traffic spikes), resulting in an on/sleep frequency that is very low.

Fig. 3.(b) reports the average value of  $AF$ , versus the values of the HW parameters, focusing on the cellular scenario. The red dashed line marks again the curve  $AF = 1$ . Also here, we can see that there is clearly a tradeoff between the zone in which using the SM option allows for a lifetime increase (area to the left) and the zone in which SM impacts negatively the lifetime (area to the right). Additionally, we report the worst (a) and best (c)  $AF$  scenarios. In the worst  $AF$  scenario, the BS  $AF$  is lower than 1 for  $\chi \leq 2$  [h/cycle]. This means that a BS exploiting an energy-efficient radio resource management that accounts also for the operating state transition frequency will be able to increase its lifetime (assuming a frequency weight  $\chi \leq 2$  [h/cycle]). In the best scenario (Fig. 3.(c)), the  $AF$  is always lower than one regardless of  $\chi$ . Similarly to the optical scenario, this case represents those BSs which are normally in SM and are powered on during peak traffic periods.

### C. Acceleration Factor Variations

It is important to consider not only the average, best, and worst  $AF$  values, but also to understand how the  $AF$  varies over the set of devices in the network. For this purpose we introduce the concept of *efficient area* defined as the area in which  $AF < 1$ . In other words, the efficient area is the triangular region below the level curve  $AF = 1$  in the bottom left region of all the plots in Fig. 2 and in Fig. 3. If a device operates in that area, then its lifetime will benefit as a result of the SM-based green strategy applied.

Fig. 4 reports the Cumulative Distribution Function (CDF) of the size of the efficient area, considering all the EDFAs and BSs deployed in the network for the optical and cellular scenario. The efficient area value was computed by varying the values of the HW parameters.<sup>2</sup> It can be seen that the size

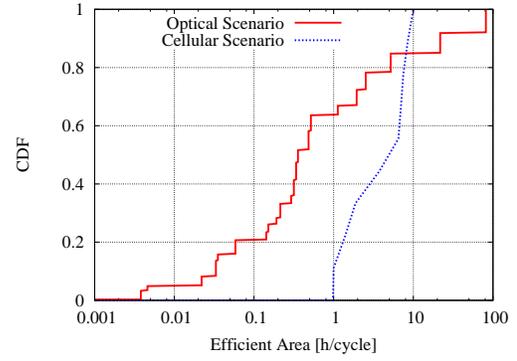


Fig. 4. Cumulative distribution function (CDF) of the size of the efficient area for the optical (Load = 150 Erlang) and the cellular scenario.

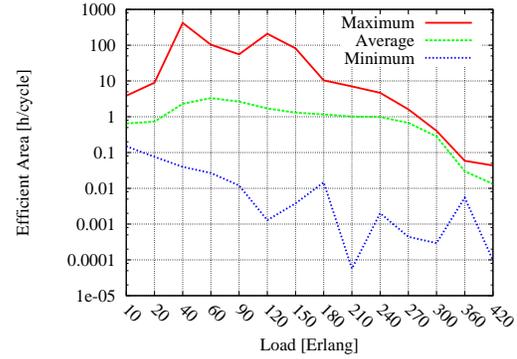


Fig. 5. Maximum, average, and minimum values of the efficient area as a function of the load for the optical scenario.

of the efficient area strongly varies over the set of devices. Moreover, the larger variation in the optical scenario compared to the cellular one is due to the larger number of devices included in the scenario, which increases the chances to put in SM the devices in the network. Thus, the impact of SM on the lifetime of a specific device might be very different, with some devices that may fail more often and other that may increase their lifetime.

We have also investigated how much the load impacts the size of the efficient area. In particular, Fig. 5 reports average, maximum and minimum sizes of efficient areas for increasing values of load. It can be observed that the size of the average efficient area does not significantly change for values of the load between 40 and 240 Erlang, suggesting that in this region WPA-LR always trades between on/sleep frequency and duration of SM. The size of the efficient area tends to decrease for higher values of load, since in this case the duration of SM is lower (i.e., more frequent SM cycles), and therefore the area in which  $AF < 1$  tends to decrease. The figure also shows that there is always a not negligible variation between the minimum and the maximum value of the efficient area for each value of load (up to 5 orders of magnitude).

Finally, Tab. II reports load variations of the size of the efficient area in the cellular scenario. More specifically, the load is changed by varying the data traffic requested by each

<sup>2</sup>The ranges of the parameters are sufficiently wide to compute properly all the areas.

TABLE II  
MINIMUM, AVERAGE, AND MAXIMUM EFFICIENT AREA SIZES [H/CYCLE]  
VS. LOAD FOR THE CELLULAR SCENARIO

	64 kbps	128 kbps	384 kbps
Min	0.91	0.78	0.99
Avg	4.37	6.95	5.28
Max	11.49	11.49	9.99

user considering 64, 128, and 384 kbps, respectively. Similarly to the optical scenario, the average size of the efficient area does not consistently vary with load. Moreover, the difference between maximum and minimum values is always about one order of magnitude for each load value, suggesting that the impact of SM on the BS lifetime is not the same for all BSs in the network.

## VI. CONCLUSIONS AND FUTURE WORK

We investigated the impact of SM-based energy efficient strategies on the lifetime of devices in cellular and backbone optical networks. In particular, we first studied the problem from an operational cost perspective, showing that the energy savings introduced by SM, in some cases, can hardly cover the reparation costs when the devices are replaced as a consequence of failures. Moreover, we developed a simple model to evaluate the impact of SM-based green strategies on the device acceleration factor. In particular, we showed that SM lowers the operating temperature thus potentially increasing the device lifetime, while frequent SM cycles have a negative effect on the lifetime. The model was used in two case studies, showing the dependency of the device lifetime variations on the specific HW and SM parameters. Additionally, we have shown that the  $AF$  varies considerably over the various devices in the network.

This work is a first step towards a more comprehensive approach in which device lifetime and energy-awareness should be jointly considered. As future work, we plan to extend our analysis considering the carbon footprint of network devices and the impact that SM might have on the switching elements in data center networks [15]. Moreover, we plan to collect measurements of the lifetime variations of real devices supporting SM. Finally, it would also be interesting to develop green techniques explicitly targeting the maximization of the devices lifetime as well as a more detailed analysis on which are the components of each device which are more susceptible to failures when SM is applied.

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