Is Green Networking Beneficial in Terms of Device Lifetime?

Luca Chiaraviglio, Pawel Wiatr, Paolo Monti, Jiajia Chen, Josip Lorincz, Filip Idzikowski, Marco Listanti, and Lena Wosinska

Luca Chiaraviglio and Marco Listanti are with the University of Rome Sapienza.

Pawel Wiatr, Paolo Monti, Jiajia Chen, and Lena Wosinska are with KTH Royal Institute of Technology.

Josip Lorincz is with the University of Split.

Filip Idzikowski is with Poznan University of Technology.

The work of Filip Idzikowski was mainly performed while he was with the University of Rome Sapienza. A preliminary version of this article was published in the *Proceedings of the Fourth IEEE Online Conference on Green Communications* [1].

ABSTRACT

This article analyzes 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, that is, their achievable energy savings might not cover the potential additional reparation costs resulting from being put in SM too frequently. Moreover, we present a model for evaluating the impact of SM on the lifetime of a device plugged into an operational network. The analysis considers two case studies (one based on the optical backbone and one on cellular networks) showing that the lifetime of a device is influenced by both the hardware parameters, which depend on the specific design of the device, and the SM parameters, which 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).

INTRODUCTION

In the past few years, the energy efficiency of communication networks has been the focus of 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 transponders, regenerators, reconfigurable optical add/drop multiplexers (ROADMs), and Erbium doped fiber amplifiers (EDFAs) into SM. 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 also trigger effects other than energy saving. In particular, SM cycles may vary the operating temperature of a device and, in turn, affect its lifetime [4].

More profoundly, temperature can impact the reliability performance of a device in different ways. For example, the lifetime of a device can be extended when its operating 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's reliability performance impacts the network operational cost in terms of extra failure reparation expenditures [4]. Therefore, it is important to make sure that the extra reparations caused by the decreased lifetime of some network devices does not exceed the potential savings from using an energy-efficient strategy.

This article 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 backbone optical networks. The objective of the study is twofold: identify the devices that may experience the highest impact on the operational cost increase due to a possible reliability performance degradation, and 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,

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and the specific energy-efficient strategy, which 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 seem to be more susceptible to reliability performance degradation from the operational cost perspective.

Lifetime Variations: Physical Phenomena

When a device goes into SM, its operating temperature may be reduced because a number of its internal components are 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 other than 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 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 the expansion of different materials within the same device differently 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, especially for solder junctions. The Coffin-Manson model [7, 8] describes the effects of material fatigue caused by cyclic thermal stress and is used to predict the number of temperature cycles a component can endure before failing. In particular, the more often a device experiences 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 this article, the lifetime variations of network devices are modeled using the Arrhenius law and the Coffin-Manson model.

Energy Efficiency vs. Lifetime Variations: An Operational Cost Perspective

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

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 trade-off 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 percent). 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}[US$/kWh] is the electricity cost, FR represents the device failure rate expressed in failure in time (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 [US$/h/member/failure] is the hourly rate of a reparation crew member, and C_{eq} [US$/failure] is the cost to buy a replacement unit of the device under reparation. For example, assuming that the monetary energy saving is US$400 and reparation costs are US$600, according to Eq. 1, the maximum allowable lifetime decrease will be 40 percent.

Table 1 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.[1] In particular, we consider two different scenarios: in the first one the device that fails has to be replaced, while in the second 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 US$0.16/kWh [12] and $US190/h/member/failure [4], respectively.

The lifetime decrease results presented in Table 1 show that in the scenario without replacement, the majority of network equipment (with the exception of EDFAs) is able to sustain a significant degradation of lifetime without a considerable impact on operational costs; that is, the maximum allowable lifetime decrease is greater than ~10 percent. In this case, the achievable energy savings from SM can easily compensate for the (possible) extra reparation costs. On the other hand, a different conclusion can be drawn in the case of EDFAs, where the

Our results indicate that the lifetime of a device is a function of its hardware characteristics, and of the specific energy efficient strategy that inevitably sets the values of the device sleep mode periods and frequencies.

[1] The input data come from [5, 9–11], 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 percent20product percent20description.pdf), Huawei eLTE3.1 DBS3900 LTE FDD Product Description (http://enterprise.huawei.com/ilink/cnenterprise/download/HW275863).

	Device type	*FR* (FIT)	*MTTR* (h)	*Pers.*	C_{eq} (kUS$)	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 Gb/s 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 Gb/s 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	10,000	6	2	10	18	0.23%	1.25%
Cellular	LTE RRU (micro/1 cell)	10,000	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)	10,000	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)	10,000	5	2	32.5	1700	7.33%	58.87%
	Macro BS (3-sector GSM, 2 transceivers/sector)	20,000	6	2	45.5	840	2.74%	37.09%

Table 1. Maximum allowable lifetime decrease analysis.

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 10 percent, suggesting that the extra reparation 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.

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 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 previously highlighted a clear trade-off between SM duration (i.e., a positive effect modeled 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:

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

where t_i^{sleep} is the amount of time spent by the device in SM (normalized to the time the device is under observation), γ_i^{on} is the failure rate at full power, γ_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's 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

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

where AF_i^{sleep} is the *AF* experienced by the device when it is always kept in SM (i.e., $AF_i^{sleep} = (\gamma_i^{sleep})/(\gamma_i^{on})$), 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 AF_i^{sleep}, the higher the gain in terms of reliability performance. χ_i is an HW parameter, defined as $\chi_i = 1/(\gamma_i^{on} N_i^F)$ [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 χ_i), which are strictly related to the HW used to build the device, and SM-related (i.e., τ_i^{sleep} and f_i^{tr}), which instead depend on the green strategy used and 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; that is, devices that are designed to better sustain frequent temperature variations are likely to fail less frequently. In addition, the duration and 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 in evaluating 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*, for example, something similar to the $\overline{AF}$ metric introduced in [1]. However, as the duration and frequency of SM periods are not the same for all devices, it might also be interesting to look into the best 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.

If sleep mode happens frequently, a device experiences frequent power state transitions between full power and sleep mode, and consequently its lifetime will be reduced.

Acceleration Factor Evaluation: A Network Level Case Study

This section evaluates the *AF* of a given set of devices when an SM-based green strategy is applied to a network. Two scenarios are considered:

- A backbone optical network using an energy-efficient routing strategy where energy is saved by setting EDFAs to SM
- 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, that is, 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 six 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 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 9.2×9.2 km^2. 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

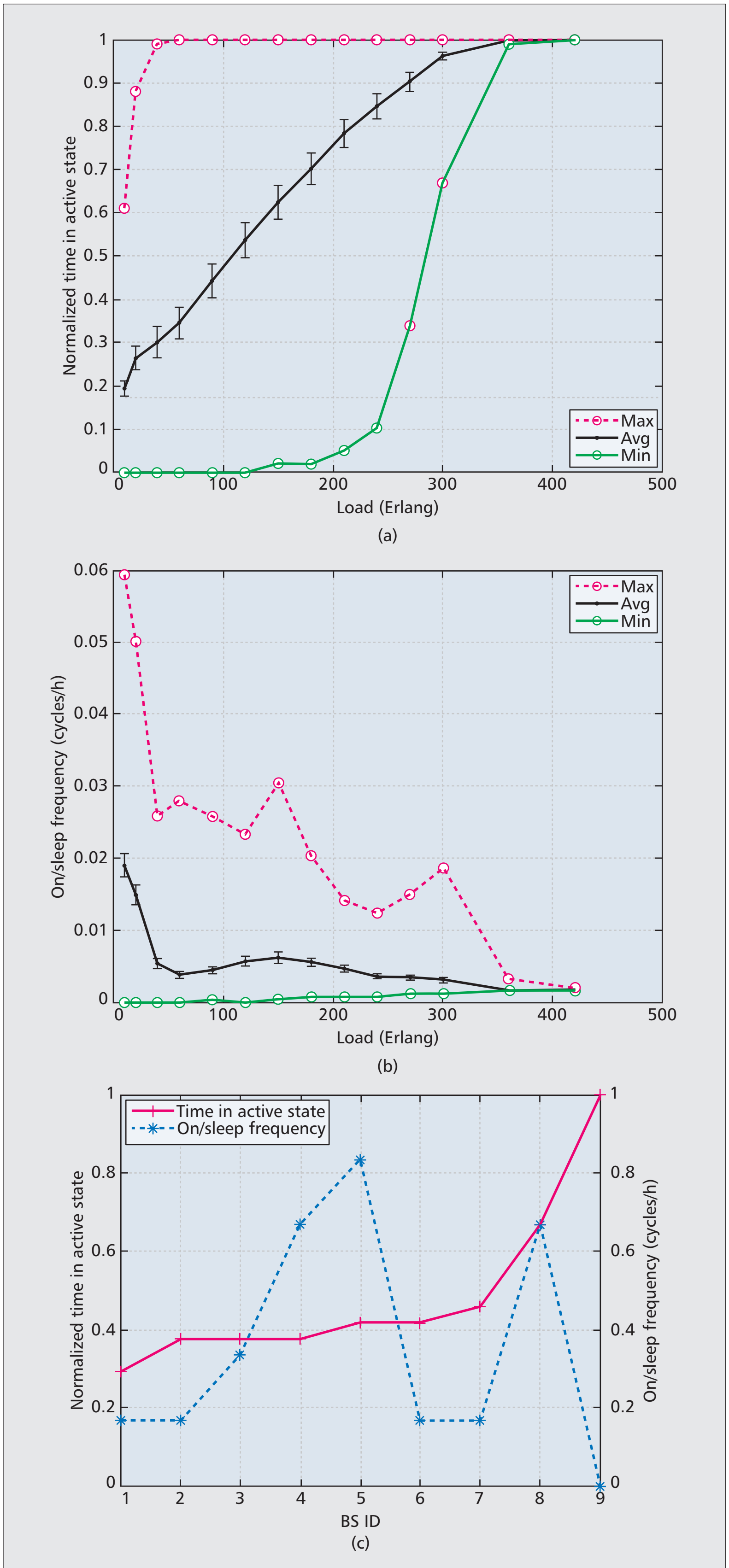

Figure 1. a) Maximum (Max), average (Avg), and minimum (Min) normalized time in active state and active/sleep switching frequency; b) for the optical scenario; c) (normalized) time in active state and active/sleep switching frequency for each base station experiencing SM cycles in the cellular scenarios.

kb/s. Moreover, we assume a day-night traffic variation with a deterministic profile over 24 h. 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 that are active in each time period. Similar 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.

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 percent. Figures 1a and 1b report the normalized time in active state and the on/sleep frequency. In particular, given the duration and 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 percent confidence level. The time in active state (reported in Fig. 1a) tends to increase with the load. This is due to the fact that EDFAs need on average to be 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 percent 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.

Figure 1b 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 that seldom change their power state, resulting in frequency almost close to zero (as expected). These EDFAs are either in full power or in SM 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, similar to the duration of SM, the on/sleep frequency also varies considerably among the EDFAs in the network.

Figure 1c reports the normalized time in active state and the on/sleep frequency for the cellular scenario. The figure presents results for each BS with at least one on/sleep cycle per day (we exclude BSs that are always at full power or in SM). Interestingly, here we can also 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.

ACCELERATION FACTOR

Since AF is a function of the HW parameters (i.e., χ 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 assume that all EDFAs or all the BSs, depending on the scenario considered, have the same HW parameters.

Figure 2b 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 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 $AF > 1$, that is, EDFAs on average are expected to fail more often than in 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} always has a positive effect on the lifetime; that is, 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 χ 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 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 EDFA lifetime. This is due to the fact that 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 χ considered in the figure). For example, this is 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.

Figure 3b reports the average value of AF vs. the values of the HW parameters, focusing on the cellular scenario. The red dashed line again marks the curve $AF = 1$. Also, here we can see that there is clearly a trade-off between the zone in which using the SM option allows for a lifetime increase (area to the left) and the zone in which SM negatively impacts 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 also accounts 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. 3c), AF is always lower than one regardless of χ. Similar to the optical scenario, this case represents those BSs that are normally in SM and are powered on during peak traffic periods.

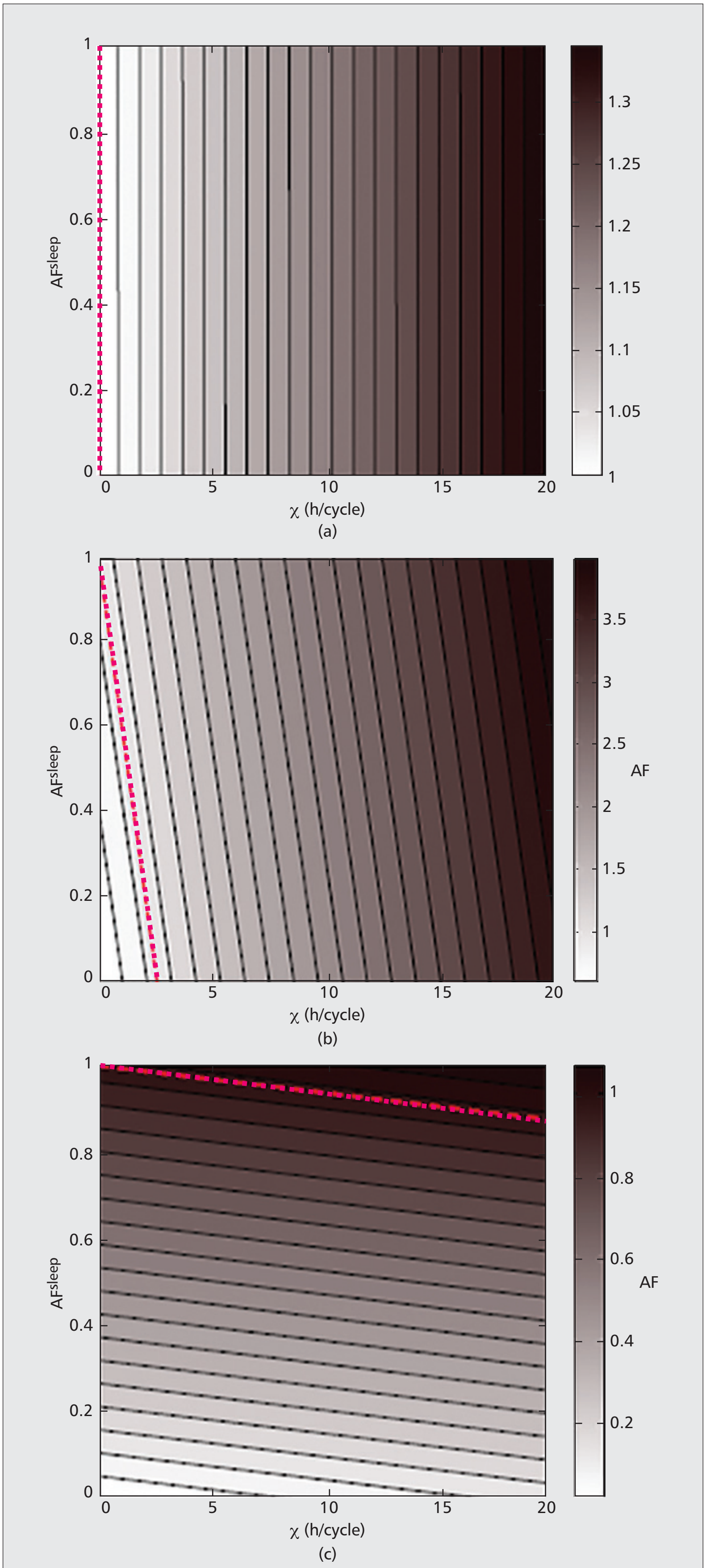

Figure 2. Acceleration factor in the optical scenario: a) worst AF value; b) average AF value; c) best AF value, as a function of χ and AF^{sleep} (load = 150 Erlang).

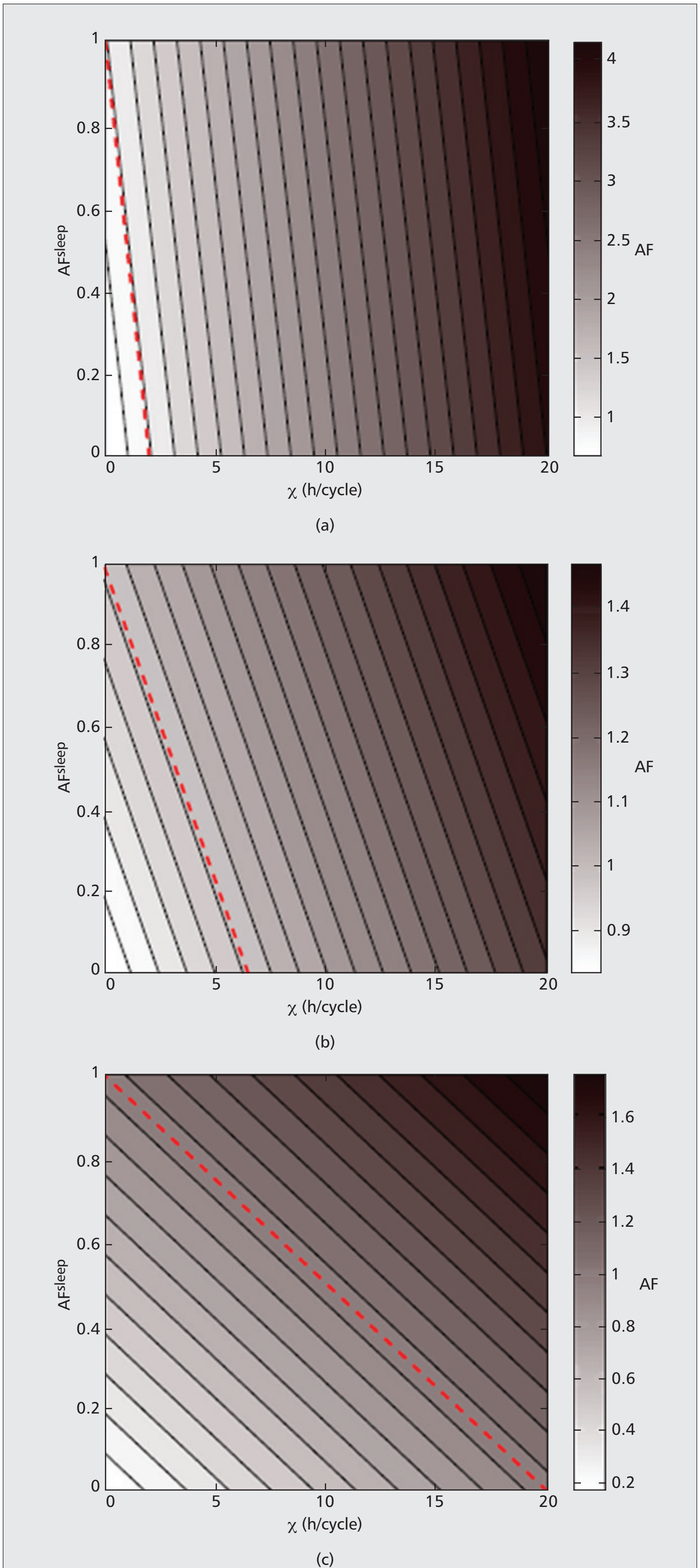

Figure 3. Acceleration factor in the cellular scenario: a) worst *AF* value; b) average *AF* value; c) best *AF* value, as a function of χ and AF^{sleep}.

Acceleration Factor Variations

It is important to consider not only the average, best, and worst *AF* values, but also to understand how *AF* varies over the set of devices in the network. For this purpose we introduce the concept of the 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 Figs. 2 and 3. If a device operates in that area, its lifetime will benefit as a result of the SM-based green strategy applied.

Figure 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 scenarios. The efficient area value was computed by varying the values of the HW parameters.[2] It can be seen that the size 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 the devices in the network in SM. 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 others 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 non-negligible variation between the minimum and maximum values of the efficient area for each value of load (up to 5 orders of magnitude).

Finally, Table 2 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 user considering 64, 128, and 384 kb/s, respectively. Similar 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 BS lifetime is not the same for all BSs in the network.

Conclusions and Future Work

We have investigated the impact of SM-based energy-efficient strategies on the lifetime of devices in cellular and backbone optical networks. In particular, we have 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

	64 kb/s	128 kb/s	384 kb/s
Min	0.91	0.78	0.99
Avg	4.37	6.95	5.28
Max	11.49	11.49	9.99

Table 2. Minimum, average, and maximum efficient area sizes (h/cycle) vs. load for the cellular scenario.

consequence of failures. Moreover, we have 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 dependence 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 toward a more comprehensive approach in which device lifetime and energy awareness should be jointly considered. As future work, we plan to extend our analysis to consider 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 devices' lifetimes as well as a more detailed analysis of which components of each device are more susceptible to failures when SM is applied.

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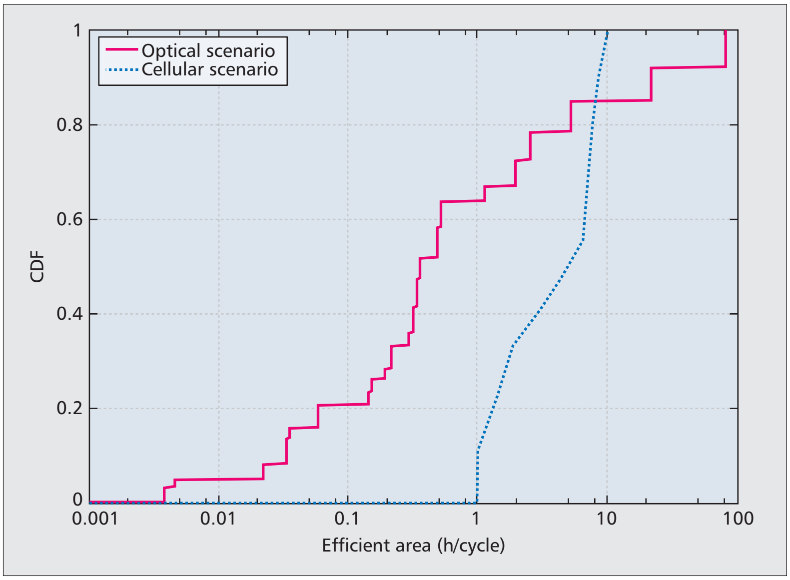

Figure 4. Cumulative distribution function of the size of the efficient area for the optical (load = 150 Erlang) and cellular scenarios.

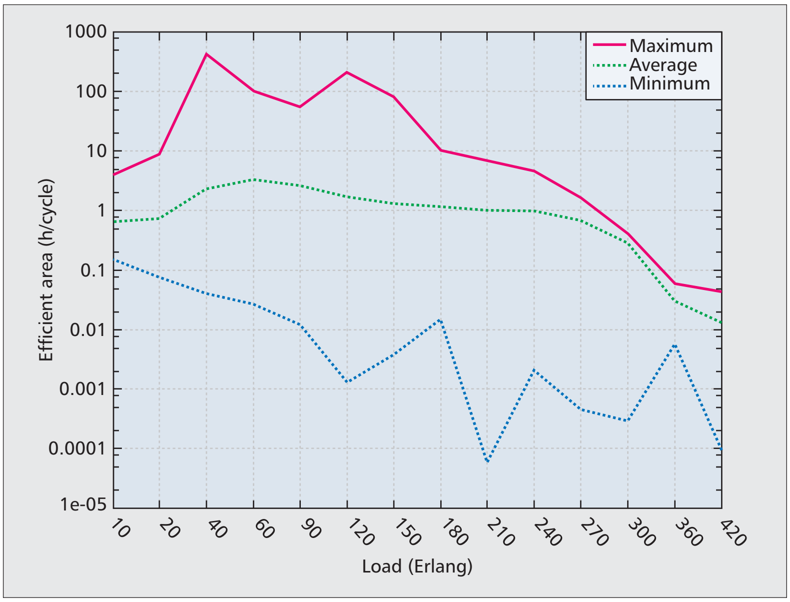

Figure 5. Maximum, average, and minimum values of the efficient area as a function of the load for the optical scenario.

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Biographies

LUCA CHIARAVIGLIO is an assistant professor in the Department of Information, Electronics and Telecommunications (DIET) of the University of Rome Sapienza, Italy. He holds a Master's degree in computer engineering and a Ph.D. in telecommunication and electronics engineering, both obtained at Politecnico di Torino, Italy. Between January 2011 and March 2013, he was first a post-doctoral researcher at the Telecommunication Network Group of Politecnico di Torino and then an ERCIM fellow at the Mascotte project of INRIA Sophia Antipolis, France. Moreover, in 2013 he was the Fabio Neri Fellow at the University of Rome Sapienza. Between August 2009 and April 2010, he was a visiting scholar at the WING group of Boston University, Massachusetts, under the supervision of Prof. Ibrahim Matta. He has coauthored more than 55 papers published in international journals and conferences, and he participates in the Program Committees of several conferences, including IEEE GLOBECOM, IEEE ICC, and IEEE Greencomm. He has also partecipated in different European projects (FP7 TREND, FP7 ECONET, FP7 BONE) and national projects (FIRB GreenNet). He is the coordinator of the national project LIFETEL (on increasing lifetime in telecommunication networks). His main research interests are in the field of sustainable networking, focusing on backbone, cellular, and data center networks.

PAWEL WIATR received his M.Sc. and Engineering degrees in telecommunications (2001) from the National Institute of Applied Sciences in Lyon, France (INSA de Lyon). Currently he is working toward his Ph.D. degree at KTH Royal Institute of Technology, Sweden. His research interests include optical networks, energy efficiency in networks, and network management. From 2005 to 2011 he worked at Comarch SA, Poland, as a technical sales manager with responsibility of proposing network management solutions (operation support systems) for network operators. Prior to that, he worked as a network administrator and research engineer at KTH in the domains of wireless networks and ubiquitous computing (interactive workspaces).

PAOLO MONTI [M] is an assistant professor at KTH Royal Institute of Technology. He received a Ph.D. degree (2005) from the University of Texas at Dallas, where he worked as a research associate until 2008. He serves on the Editorial Board of *Springer Photonic Network Communications* and has co-authored more than 100 technical papers, with three best paper awards. His main research interests are within the networking aspects of all-optical networks, while part of his work recently focused on the architectural and control challenges posed by next generation mobile communication (i.e., 5G) on optical transport networks.

JIAJIA CHEN [SM] received a B.S. degree (2004) from Zhejiang University, China, and a Ph.D. degree (2009) from KTH Royal Institute of Technology, Sweden. She is an associate professor in the Optical Networks Lab (ONLab) at KTH. She is a co-author of over 100 publications in international journals and conferences in the area of optical networking. Her main research interests are optical transport and interconnect technology supporting the future 5G and cloud environment. She has been involved in various European research projects like FP7 projects Integrated Project-Optical Access Seamless Evolution (IP-OASE) and Integrated Project-The Distributed Core for Unlimited Bandwidth Supply for All Users and Services (IP-DISCUS), and EIT-ICT projects (e.g., mobile backhaul, M2M, and Xhaul). Moreover, she is principal investigator/co-principal investigator of several national research projects funded by the Swedish Foundation of Strategic Research (SSF) and Swedish Research Council (VR). She has been involved in many professional activities including serving on the TPCs of many conferences (e.g., OFC, Photonics in Switching), as well as being a reviewer for scientific journals and project proposals. Currently, she is serving as an Associate Editor of the *Journal of the Franklin Institute*, Elsevier (impact factor: 2.260).

FILIP IDZIKOWSKI is an assistant professor at Poznan University of Technology, Poland. He received his Ph.D. (Dr.-Ing.) from the Technical University of Berlin, Germany, in 2014, and was with University of Rome Sapienza, for half of 2014. His main research interests include power consumption of multi-layer core networks, traffic modeling, protection, and routing.

JOSIP LORINCZ [M] received his M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Split, FESB, Croatia, in 2002 and 2010, respectively. He was a visiting researcher at the Advanced Network Technologies Laboratory (ANTLab) of the Politecnico di Milano, Italy. He is co-chair of the Symposium on Green Networking and Computing, organized in the framework of the SoftCOM conference. He serves as a TPC member for many international scientific conferences, and a reviewer for scientific journals and project proposals. He was recognized as an outstanding young researcher by the Croatian Academy of Engineering in 2013. His current research interests include energy-efficient wireless and wired networks, optimization in telecommunications, and advanced design of heterogeneous communication networks. He is a member of ACM and the first president of the Croatian ACM Chapter.

MARCO LISTANTI is a full professor in telecommunication networks at the Department of Information of the University of Rome Sapienza. Since November 2013 he has been Dean of the Faculty of Information Engineering, Informatics and Statistics. In about 35 years of activity, his research interest has been mainly focused on the area of architectures and performance evaluation of telecommunication networks. He has participated in national and international standardization commissions and working groups in the field of telecommunication networks (CCITT, ETSI, ITU, IETF, etc.). He has coordinated the activity of many national and international study and research projects in the frame of the programs RACE, ACTS, ITS, COST, ESA, MIUR. He is an author of more than 300 papers, published in the most important scientific magazines and journals, and the proceedings of the main international conferences in the area of telecommunications.

LENA WOSINSKA [SM] received her Ph.D. degree in photonics and her Docent degree in optical networking from KTH Royal Institute of Technology, where she is currently a full professor of telecommunication in the School of Information and Communication Technology (ICT). She is founder and leader of the Optical Networks Lab (ONLab) at KTH/ICT. She has worked on several EU projects and coordinated a number of national and international research projects. Her research interests include fiber access networks, energy-efficient optical networks, photonics in switching, optical network control, reliability and survivability, and optical data center networks. She has been involved in many professional activities, including serving as an Associate Editor and Guest Editor of IEEE, OSA, Elsevier, and Springer journals, serving as General Chair and Co-Chair of several IEEE, OSA, and SPIE conferences and workshops, serving on TPC of many conferences, as well as being a reviewer for scientific journals and project proposals.