Optimal Lifetime-Aware Operation of Green Optical Backbone Networks

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***Abstract*—This paper targets the lifetime-aware management of a set of Optical Line Amplifiers (OLAs) in an optical network exploiting Sleep Mode (SM) in order to save energy. We first present a simple model to predict the OLA lifetime. We then provide different Mixed-Integer Linear Programming (MILP) formulations which jointly consider energy saving and lifetime. The proposed MILP formulations are then solved on different realistic scenarios, by taking into account spatial and temporal variations of traffic demands. Results show that our lifetime-aware approach outperforms classical energy saving Integer Linear Programming (ILP) formulations, which instead tend to notably decrease the OLA lifetime. More important, the proposed approaches can achieve a good lifetime performance without consuming significantly more energy than purely energy-aware strategies.**

***Index Terms*—Optical network operation; optical line amplifiers; lifetime and energy trade-off.**

I. Introduction

THE electricity consumed by the Information and Communication Technology (ICT) sector is constantly increasing [2], a trend that is not expected to change or improve in the future. The power consumption (and consequently the electricity costs) of the ICT sector is shared among a variety of devices, including end hosts, servers, routers, switches, optical devices, and access network ones (e.g., e-NodeBs and Wireless LAN access points). Clearly, these devices are managed by different entities (i.e., end users, content providers, and telecom operators). In this context, a backbone optical network, while not being the highest power consumer in the ICT sector, may still consume 15-20 kW just to keep in Active Mode (AM) the optical core network equipment [3]. Moreover, the cost for powering optical backbone networks is likely to increase in the near future [2]. More specifically, future networks will be driven by very strict Quality of Service (QoS) constraints (e.g., in terms of bandwidth and delay) required by the upcoming 5G paradigm [4, 5]. These new 5G service requirements will force operators to install high performance devices, leading to an additional increase of the total power consumed (and, consequently, the electricity cost) to operate their networks. As a result, the interest that optical backbone operators have in limiting the power consumption of their deployed devices is constantly increasing.

Nowadays, backbone devices consume an amount of power that does not depend on the amount of traffic flowing through them [6, 7]. To overcome this issue, several approaches have been proposed to make their energy consumption proportional to the traffic load [8]. Among the different solutions, one of the most promising one is the use of a Sleep Mode (SM) state in network devices in order to save energy. In particular, the main idea of a SM-based green approach is to manage the power state of one or more devices in a network by taking advantage of the fact that traffic requests are not constant but tend to notably vary over time. For example, it may be possible to put most of the devices into SM during off-peak hours (i.e., when the traffic is low), and activate them again when the traffic level increases. As a result, the number of devices always active is (on average) reduced and less power is required to operate a network [9]. On the other hand, a green strategy based on SM requires particular attention in order to guarantee that those devices remaining in AM are still able to accommodate the traffic requests.

The topic of power saving in telecommunication networks exploiting SM has been deeply investigated in the last years (see e.g., [10, 11] for detailed surveys). Although the energy saving benefits of SM are clear and well understood, their effect in terms of additional operator costs is still an open issue. For example, the authors of [12] claim that SM has an implication on the risk awareness from a business point of view. Intuitively, the risk of having failures affecting the QoS level is increased when SM is applied to backup resources. At the same time, the application of SM has a direct impact on the lifetime of network devices [13]. In particular, there are two opposite effects triggered by the application of SM. The lifetime of a network device tends to benefit from being in SM as a consequence of the reduction of the operational temperature experienced by its components. However, frequent transitions between AM and SM lead to temperature variations that tends to deteriorate the lifetime. In this scenario, when a network device fails, it has to be repaired (or even replaced with a new one in the worst case). Hence, these additional maintenance operations result in an additional operational cost for the operator. In the worst case (i.e., when adopting very aggressive SM policies that trigger frequent power state transitions), the electricity savings obtained by SM may be even surpassed by the maintenance costs triggered by the device lifetime reduction [14]. Therefore, it becomes clear that the impact of SM on the lifetime variation of network

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devices should be carefully taken into account in the process of deciding when and for how long to put a device into SM.

When considering this problem, several questions arise, such as: is it possible to save energy in an optical network using SM while still limiting the possible device lifetime degradation? What is the impact that a specific network scenario and the traffic variations have on the energy and the device lifetime performance? The goal of this paper is to answer these questions. In particular, we focus on a backbone network composed by Optical Cross-Connects (OXCs) interconnected by fiber links. Each fiber link is equipped with a set of OLAs used to amplify the optical signal. OLAs support SM operations to reduce their power consumption and are subject to lifetime variations triggered by SM activation/deactivation. Our goal is to account for the temporal and the spatial variations of the traffic and to formulate an optimization problem that minimizes both the total network energy consumption and the OLAs lifetime degradation. This is done while ensuring that all the traffic demands are satisfied. It is important to note that with the proposed formulation it is possible to explicitly limit the lifetime degradation of OLAs while still allowing for energy savings. This aspect is of mandatory importance for a backbone operator, which is interested in increasing its income while, at the same time, reducing its costs (i.e., in terms of reparation/replacement and energy consumption). Results, obtained from different representative case studies, show that the lifetime-energy trade-off can be efficiently controlled. Moreover, we also show that approaches focused only on energy minimization tend to notably decrease the OLAs lifetime.

The rest of the paper is organized as follows. The related work is reviewed in Section II. The model used to compute the OLA lifetime variations is reported in Section III. Section IV introduces the problem formulation. The performance of the proposed solutions is assessed in Section V. Finally, Section VI summarizes the paper and provides an outline of the future work.

II. Related Work

Different works investigated the topic of energy efficiency in optical networks via the activation/deactivation of OLAs. They focused on both network design (see e.g., [15]), and network operation (see e.g. [16]). However, only a few of them explicitly considered the impact of SM-based policies on the OLA lifetime. A very simple approach to indirectly take into account the OLA lifetime is to reduce the cost of network reconfigurations (e.g., the number of power state transitions experienced in the network between two consecutive time periods). In the following, we survey the works taking into account reconfiguration costs at the optical layer. Then, we review the works that explicitly consider SM and device lifetime at the optical or Internet Protocol (IP) layer.

A. Sleep modes and reconfiguration costs

To the best of our knowledge, [17] is the only work taking into account reconfiguration costs in the optical layer. The paper proposes an ILP formulation for optical networks controlled with Generalized MultiProtocol Label Switching (GMPLS) with the goal of reducing the energy consumption of transponders and OLAs. The number of lightpaths to reroute is minimized in two versions of the objective function of the ILP model, thus indirectly influencing also the number of cycles between power states. However, no evaluation of the OLA lifetime is performed.

Focusing on the approaches jointly targeting the IP and the optical layer, an approach called top-down scheme is proposed in [18, 19]. This MILP-based scheme first calculates the minimal number of lightpaths, line cards and chassis needed to support traffic demand during traffic peak time. Then (going down from the top), the set of ligithatphs, line cards, and chassis for low traffic conditions are calculated as sub-sets of the ones used for high traffic demands. However, the OLAs (and their lifetime) are not considered.

Finally, the work in [20] focuses on the limitation of the number of network reconfigurations (i.e., referred to as events). A network configuration in the considered IP-over-Wavelength Division Multiplexing (WDM) network determines whether devices such as line cards, IP routers and OLAs are to be put into SM. The proposed method finds not only network configurations with minimum network power consumption, but also limits the number of times the network needs to be reconfigured. No evaluation of the OLAs lifetime is performed though.

B. Sleep modes and device lifetime

The first work (to the best of our knowledge) directly investigating the impact of SM on the lifetime of backbone devices is [21]. The authors detail a device lifetime model by taking into account the impact of temperature decrease and the impact of thermal cycling. Furthermore, the paper proposes an analytical network model to compute the network failure Acceleration Factor (AF), a parameter used to measure the mean lifetime decrease/increase of a device. An evaluation of AF variations of IP line cards (i.e., as the result of the application of an energy saving algorithm called DAISIES) is performed, without targeting an explicit minimization of this parameter. Differently from [21], in the current work we investigate the impact of SM in optical network devices. More specifically, we study the AF variations of OLAs. In addition, the strategies proposed in this paper directly target the minimization of the AF of the OLAs.

Additionally, the authors of [22] distinguish between large thermal cycles (due to AM-SM switching) and small thermal cycles (due to workload behavior), and focus on the former ones using the Coffin-Manson equation. A dynamic programming approach (a technique to solve combinatorial optimization problems) is suggested for managing network devices. The approach tries to minimize the Operational Expenditure (OpEx) as a result of regular network operation and the number of transitions between network states. Two simple examples are presented showing the effects of thermal cycling. However, no extensive experiments are performed. Similar to [21], the optical layer is not considered.

In [14, 23], the authors perform a device-based and network-based analysis of energy efficiency versus reliability performance in a network using the Weighted Power-Aware Lightpath Routing (WPA-LR) strategy, an algorithm which is designed to achieve energy efficiency in an optical network. In contrast to [14, 23], this work jointly considers the lifetime value together with energy in the objective function of the proposed strategies, trying to minimize its variations.

The works in [13, 24] study the impact of SM on the lifetime of network devices (i.e., OLAs in the optical backbone networks and base stations in cellular networks) when energy saving approaches are used. Results show that a careful management of the AM-SM transitions needs to be put into place, otherwise large lifetime degradations should be expected. Differently from these two works, in this paper we propose a strategy which directly targets the minimization of the OLA lifetime degradation.

The impact of introducing lifetime awareness in backbone IP networks is considered in [25, 26]. More in depth, the problem of the maximization of the value of the average lifetime of line cards is formulated using a MILP [25]. Additionally, a simple heuristic is proposed in [26]. However, both these works are focused on the IP layer, and do not consider the optical one. Our work instead complements [25, 26] by proposing a framework to concurrently maximize lifetime and energy saving in the optical layer.

III. Lifetime Model

In this section, we present a model to predict the lifetime of an OLA subject to power state changes. More in depth, we focus on the main physical phenomena related to power that may influence the OLA lifetime, defined as the amount of time between one failure and the following one. In this work, we focus on failures affecting the functionality of the entire OLA.[1] Thus, when a failure occurs, the OLA has to be repaired or, in the worst case, to be replaced with a new one. In the following, we briefly review the main effects impacting the lifetime variations, and then we present model to measure them. We refer the reader to [13] for a more detailed explanation of such phenomena and of the lifetime model.

A. Impact of Sleep Mode Activation

When an OLA is in SM, most of its components are powered off, resulting in possible energy savings compared to the case in which the device is in AM. One of the side effects of being in SM is the fact that the operating temperature of the device is reduced. The impact of temperature variation is in general a well studied phenomenon for the lifetime of micro processors and memories (see e.g., [27, 28]). More in depth, when temperature decreases, the lifetime tends to increase. This effect is also confirmed by empirical models, such as the Arrhenius law [29]. The lower is the temperature, the higher is the lifetime. Therefore, if a lower operating temperature would be the only effect taken under consideration, SM activation would be beneficial for the OLA lifetime.

[1] We leave the investigation of more detailed lifetime models (e.g., tailored to the single OLA components) as future work.

B. Impact of Sleep Mode - Active Mode Transitions

Another phenomenon affecting the OLA lifetime is triggered by the transition between power states. More in depth, network devices are designed to be always powered on and working at a given temperature. When SM is set, the temperature on the device is decreased. Similarly, when the OLA enters AM from the SM state, the temperature is increased. These power cycles, which influence the temperature, have an impact on the lifetime. More specifically power state transitions, which involve temperature variations, may trigger fatigue, cracking, and as a result failures [30]. In this scenario, the higher is the number of power cycles experienced by the OLA, the lower is its lifetime. This effect is captured by well known models, such as the Coffin-Manson [31, 32], or the Norris-Landzberg [33] equations. Thus, we can see that there are two different effects impacting the lifetime of an OLA: a positive one (i.e., the increase of lifetime when the OLA is in SM), and a negative one (i.e., the lifetime decrease due to power state changes). In the following we define a model to jointly take into account these phenomena.

C. AF Lifetime Metric

Rather than working directly with lifetimes, we adopt a metric called (lifetime) *Acceleration Factor (AF)* [34]. The AF is defined as the ratio between the mean lifetime when an OLA is always kept in AM (γ^{on}), and the lifetime when an OLA is periodically set into SM (γ^{tot}). In this way, we are able to express the lifetime increase/decrease w.r.t. a reference case, the OLA always kept in AM. The AF is defined as:

$$AF = \frac{\gamma^{on}}{\gamma^{tot}} = 1 - (1 - AF^{sleep})\frac{\theta}{T} + \chi\frac{c}{2}, \qquad (1)$$

where $AF^{sleep} \in (0, 1)$ is a HardWare (HW) parameter defining the AF experienced by an OLA when it is always kept in SM (by neglecting the effects of power state transitions), θ is the total amount of time spent by an OLA in SM, T is the total period of time under consideration, $\chi > 0$ is a HW parameter representing the AF variations caused by a single AM-SM cycle, and $\frac{c}{2}$ is the total number of AM-SM cycles an OLA goes through. The model is defined taking into account the different effects influencing the OLA lifetime, by assuming that the failures are statistically independent from each other, and their effect is additive [35]. If AF > 1, the OLA lifetime is decreased compared to the full power case. If AF < 1, the lifetime is increased.

By looking more in detail to Eq. (1), we can see that the lifetime variation is influenced by HW parameters (AF^{sleep} and χ) that depend on the components used to build the OLA, and by parameters related to the SM policy (θ and $\frac{c}{2}$) whose impact can be limited by wisely choosing the length and frequency of the AM-SM cycles, i.e., with a lifetime-aware SM strategy. In particular, the AF for an OLA always kept in SM (i.e., $\theta = T$ and $c = 0$) is equal to AF^{sleep}. On the contrary, the AF for an OLA always in AM (i.e., $\theta = 0$ and $c = 0$) is equal to 1. Additionally, the AF for an OLA experiencing AM and SM power states can be higher or lower than 1. Therefore, both the HW parameters and the proposed SM strategy play

TABLE I
MILP MODELS MAIN NOTATION.

	Symbol	Unit	Description
Input Parameters	V	-	Set of nodes
	E	-	Set of physical links, each link $(i, j) \in E$ from node $i \in V$ to node $j \in V$
	K_{ij}	-	Set of fiber links on the physical link $(i, j) \in E$
	OLA_{ijk}	-	Set of OLAs installed on the fiber link (i, j, k), $(i, j) \in E, k \in K_{ij}$
	X_{ijk}	[units]	1 if fiber link (i, j, k) was in AM during the previous time period, and 0 otherwise
	W_{ijk}	[units]	Total number of wavelengths available on fiber link (i, j, k)
	C_{ijk}	[units]	Total number of power state transitions of fiber link (i, j, k) up to the previous time period
	Θ_{ijk}	[h]	Total time in SM spent by fiber link (i, j, k) up to the previous time period
	t^{sd}	[units]	Number of lightpath requests from node s to node d $(s, d \in V)$ during current time period
	δ_t	[h]	Time duration of current time period
	AF^{sleep}_{ijkq}	[units]	AF when the OLA q on fiber link (i, j, k) is in SM
	PL_{ijkq}	[Watt]	Power consumption for the OLA q when fiber link (i, j, k) is in AM
	χ_{ijkq}	[1/h]	HW parameter accounting for the AF increase due to power state transitions for OLA q on fiber link (i, j, k)
	T	[h]	Total observation time
	α	[Watt]	Lifetime-aware vs. energy-aware weighting factor used by LAF-EA and LAF-TH
	γ	[units]	Threshold used by LAF-TH to limit the maximum AF allowed for each OLA in the network
	M	[units]	A constant great number, which must be greater than any AF_{ijkq} value
Variables	f^{sd}_{ijk}	[units]	Number of used wavelengths for the lightpaths requested from node s to node d routed through fiber link (i, j, k)
	f_{ijk}	[units]	Total number of used wavelengths on fiber link (i, j, k)
	x_{ijk}	[units]	1 if fiber link (i, j, k) is in AM during the current time period, 0 otherwise
	z_{ijk}	[units]	1 if fiber link (i, j, k) has a power state transition between the current time period and the previous one, 0 otherwise
	c_{ijk}	[units]	Total number of power state transitions of fiber link (i, j, k) up to the current time period
	θ_{ijk}	[h]	Total time in SM for fiber link (i, j, k) up to the current time period
	AF_{ijkq}	[units]	Total AF of OLA q on fiber link (i, j, k)
	h_{ijk}	[units]	1 if the fiber link (i, j, k) has OLA with AF greater than γ, 0 otherwise

a crucial role in determining the lifetime increase/decrease of an OLA.

Note that our AF metric is able to predict the lifetime increase/decrease for an OLA on average. More in depth, the presented model does not consider single failure events, but rather their average impact on the device lifetime. This is inline with the related work on reliability prediction (see e.g., [36]). In the following, we define a methodology to optimize the weighted sum of AF and energy in an optical backbone network.

IV. Optimal Formulations

The overall objective of our work is to derive a number of optimal strategies able to minimize the value of the OLAs lifetime AF increase, while guaranteeing that the traffic requirements (i.e., number of lightpaths to be provisioned) are always met, and still being able to reduce the total network energy consumption. The value of the AF is minimized in order to limit the impact of possible reparation/replacement costs as a consequence of the OLAs lifetime reduction.

We consider a multi-period lightpath establishment problem in which the traffic requirements vary over time. We assume that the total period of time under consideration is divided into smaller time periods. For each one of them we assume to know the traffic matrix storing the number of lightpaths that need to be provisioned between each node pair in the network. Moreover, each lightpath request occupies the entire bandwidth of a wavelength channel. In addition, fiber links equipped with OLAs are considered. Therefore, the term "fiber link power state" refers to the power state (i.e., AM or SM) of all the OLAs installed along the considered fiber link.

In such a scenario, a multi-period lightpath establishment strategy can take advantage of the spatial and temporal variations of the traffic by: (1) selecting where to set up lightpaths (i.e., on which route and on which wavelength), and (2) deciding which link to deactivate and put the corresponding OLAs into SM. The resulting strategy is required to be both energy-aware (i.e., by maximizing the number of OLAs in SM) and lifetime-aware (i.e., by limiting the AF increase).

In this work, the AF variations are computed according to the model presented in Section III. We develop three different MILP formulations, namely Lifetime-Aware Formulation (LAF), LAF-EA, and LAF-TH. More specifically, LAF considers only the minimization of the average lifetime degradation of the OLAs in the network (as a result of periodically going into SM). Since the AF and the energy minimization are conflicting objectives (due to the fact that a purely power saving approach may increase the number of power state transitions), LAF-EA allows for a trade-off between the OLA lifetime degradation and the maximization of network energy saving. Finally, since LAF considers only the value of the average AF over the set of OLAs in the network (while the AF of a single OLA may differ from the average), LAF-TH allows to set a threshold that limits the AF degradation of each individual OLA in the network. The following subsections are devoted to the formal description of each one of these formulations, while the main notation is reported in Tab. I.

A. Lifetime-Aware Formulation (LAF)

The goal of LAF is to limit the lifetime degradation of the OLAs in the network. The inputs of LAF are the physical network topology (i.e., nodes and fiber-link connectivity), the set of lightpath requests to be established in the network in the current time period (i.e., the traffic matrix), the fiber links power state at previous time period [2] , the time spent in SM, and the number of AM-SM transitions up to the previous time period. The problem can be formalized as follows:

$$\text{minimize} \quad \frac{\sum_{i=1}^{|V|}\sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ij}|}\sum_{q=1}^{|OLA_{ijk}|} AF_{ijkq}}{\sum_{i=1}^{|V|}\sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ij}|}|OLA_{ijk}|}. \tag{2}$$

Subject to:

$$\sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ij}|} f_{ijk}^{sd} - \sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ji}|} f_{jik}^{sd} = \begin{cases} t^{sd} & , i = s \\ -t^{sd} & , i = d \\ 0 & , i \neq s, d \end{cases}, \tag{3}$$
$$\forall s, d, i \in V$$

$$f_{ijk} = \sum_{s=1}^{|V|}\sum_{d=1}^{|V|} f_{ijk}^{sd}, \quad \forall (i,j) \in E, \forall k \in K_{ij} \tag{4}$$

$$f_{ijk} \leq W_{ijk} \times x_{ijk}, \quad \forall (i,j) \in E, \forall k \in K_{ij} \tag{5}$$

$$\begin{cases} x_{ijk} - X_{ijk} & \leq z_{ijk} \\ X_{ijk} - x_{ijk} & \leq z_{ijk} \end{cases}, \quad \forall (i,j) \in E, \forall k \in K_{ij} \tag{6}$$

$$c_{ijk} = C_{ijk} + z_{ijk}, \quad \forall (i,j) \in E, \forall k \in K_{ij} \tag{7}$$

$$\theta_{ijk} = \Theta_{ijk} + (1 - x_{ijk})\delta_t, \quad \forall (i,j) \in E, \forall k \in K_{ij} \tag{8}$$

$$AF_{ijkq} = \left[1 - \left(1 - AF_{ijkq}^{sleep}\right)\frac{\theta_{ijk}}{T} + \chi_{ijkq}\frac{c_{ijk}}{2}\right], \tag{9}$$
$$\forall (i,j) \in E, \forall k \in K_{ij}, \forall q \in OLA_{ijk}.$$

The objective function (2) minimizes the AF averaged over all the OLAs in the network in the current traffic period. The constraints (3) ensure the flow conservation for all the lightpaths provisioned. The constraints (4) count the total number of wavelengths used on fiber link (i, j, k). The constraints (5) make sure that when fiber link (i, j, k) is in AM, it cannot be traversed by more lightpaths than the maximum number of wavelength available. The constraints (6) compute the number of power state transitions w.r.t. previous time period for all the OLAs on fiber link (i, j, k). The constraints (7) and (8) count, for a given fiber link (i, j, k), the total number of power state transitions and the total time spent in SM from the initial time period up to the current time period, respectively. The constraints (9) compute the AF values for each OLA up to the current time period. As it can be noticed, in the LAF model decisions on the power state of the OLAs in a given time period are taken based only on the knowledge of the traffic during current time period and of the past power state transitions history. The knowledge about the traffic matrix in future time periods is not assumed to be known.

B. Lifetime-Aware Formulation with Energy-Awareness (LAF-EA)

The LAF formulation minimizes the average AF over all the OLAs. The amount of the power consumed is not considered at all. However, since power saving and AF minimization may be two opposite goals, it may end up that a lifetime-aware approach may save less power than a pure power-aware one. To this end, we have therefore modified the LAF formulation

[2]We assume that all the OLAs are in SM during the first time period.

by jointly considering lifetime and power in the objective function. More formally, the LAF-EA problem is defined as:

$$\text{minimize} \quad \alpha \sum_{i=1}^{|V|}\sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ij}|}\sum_{q=1}^{|OLA_{ijk}|} AF_{ijkq} \tag{10}$$
$$+ \sum_{i=1}^{|V|}\sum_{j=1}^{|V|}\sum_{k=1}^{|K_{ij}|} x_{ijk} \sum_{q=1}^{|OLA_{ijk}|} PL_{ijkq},$$

subject to the constraints (3)-(9).

The objective function (10) is composed of two terms. The first one is the sum of the AF of all the OLAs in the network. The second one is instead the power consumed by all the active OLAs. [3] The AF term is then weighted with a parameter α [W], which allows to trade between power minimization ($\alpha = 0$) and AF minimization ($\alpha >> 0$).

C. Lifetime-Aware Formulation with ThresHolds (LAF-TH)

The models presented so far optimize the value of the average AF of the OLAs in the network. However, the AF experienced by the single devices may differ consistently from the one averaged over all the devices [13]. Therefore, it would be also useful to provide a solution in order to control the AF of the single devices, e.g., to ensure that the AF of each OLA is below a maximum value. To solve this issue, we have developed the LAF-TH formulation, by introducing a threshold to limit the maximum AF allowed by each OLA.

More formally, LAF-TH uses the objective function described in (10) (i.e., the same objective function as LAF-EA), subject to the constraints (3)-(9) and the following additional constraints:

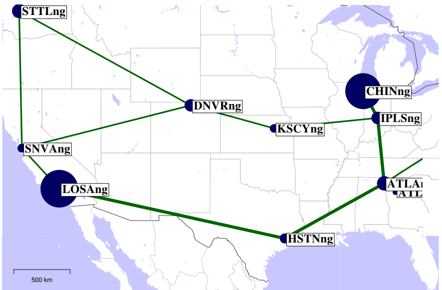
$$AF_{ijkq} - \gamma \leq M \times h_{ijk}, \tag{11}$$
$$\forall (i,j) \in E, \forall k \in K_{ij}, \forall q \in OLA_{ijk},$$
$$X_{ijk} + h_{ijk} \leq x_{ijk} + 1, \forall (i,j) \in E, \forall k \in K_{ij}. \tag{12}$$

The constraints (11) check if the AF value of each single OLA in the fiber link (i, j, k) is below the threshold γ. If any of the OLAs in the link is above the threshold, h_{ijk} will assume value 1, and 0 otherwise. The constraints (12) make sure that if a given fiber link is in AM it can be put into SM only if such power state change does not violate the threshold.

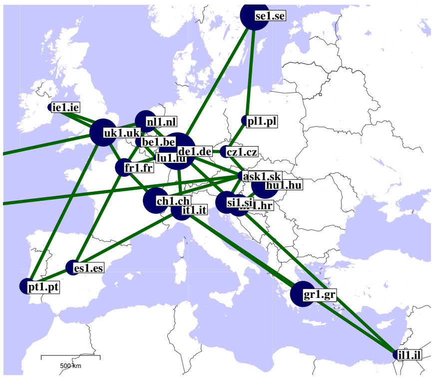
V. Performance Assessment

This section assesses the performance of the three lifetime-aware MILP models (i.e., LAF, LAF-EA, and LAF-TH) presented in Section IV. The results are obtained via simulation, i.e., by optimally solving the presented formulations across different scenarios. In particular, the first part of the section describes the scenarios used in the performance evaluation work, while the second part presents and discusses the simulation results.

[3]Since the number of lightpath requests to be established between each node pair in the network is an input of the problem, the number of active transponders needed to established the required number of lightpaths is constant and cannot be changed. As a result the only way to reduce the power required to satisfy a given traffic matrix is to try to activate as few OLAs as possible. Deactivation of idle lightpaths (with transponders) can be done independently of the MILP formulations presented in this work.



(a) Abilene topology designed in [3].



(b) Géant topology designed in [3].

Fig. 1. Optical network topologies (link widths proportional to the number of installed fibers, one node of the Géant topology located in NY, USA).

A. Description of Network Scenarios

Using realistic scenarios is important for a proper evaluation of the proposed strategies. Below we provide more detailed information on: (1) the optical network topologies considered, (2) how the temporal and spatial variations of the traffic have been generated (i.e., how the set of multi-period traffic matrices have been built), and (3) the assumptions used for the technology parameters (e.g., SM related HW parameters, and the power consumption values).

Optical network topologies: We assumed as input the physical topology of the Abilene and of the Géant network. These topologies are the result of the network design work (based on a MILP formulation) presented in [3] (see Fig. 1) that provides, for each topology, the total number of transponders and line cards installed in each network node, the number of fibers (with OLAs) installed in each network link, and the number of wavelengths per fiber[4].

Traffic data: In this work we consider the day/night traffic variations over a period of 15 days. In each day we assume to have a high-traffic period (i.e., between 06:00 am and 11:45 pm) and a low-traffic period (i.e., between 12:00 am and 05:45 am). Therefore, we consider two time slots for each day. The choice of the lengths of the low- and high-traffic periods is dictated by the relatively long times needed to power on an OLA, full network operation targeted during a day (when traffic is expected to reach its peak), and energy saving targeted at night (when traffic is expected to be relatively low). As for the set of lightpaths (i.e., the traffic matrix) to be established during the high- and low-traffic periods in each of the 15 days in our experiments, we considered two options: (1) a set of traffic matrices based on real traffic measurements, and (2) a set of traffic matrices with random perturbations, derived by inserting a degree of randomness into the measurement-based traffic matrices.

The set of traffic matrices based on real traffic measurements are derived from the logical topology design results presented in [40]. More specifically the work [40] takes as input the IP traffic measured on 27/08/2004 (for the Abilene network) and on 10/06/2005 (for the Géant network) and, after breaking down these traffic measurements into 15-minute-long periods, returns 96 logical topology design results [5], one for each period. The traffic matrix (t^{sd}, $\forall s, d \in V$) for the high-traffic period used in our work is derived from these results by choosing node-pair-by-node-pair the maximum number of lightpaths to be established out of all the logical topology design results belonging to the 06:00 am – 11:45 pm period. Similarly, the traffic matrix for the low-traffic period is derived by analyzing the design results from [40] in the 12:00 am – 05:45 am period. Once the high- and low-traffic matrices have been computed, they are used in each of the 15 days in our experiments.

The set of traffic matrices with random perturbations is derived by inserting a degree of randomness into the traffic matrices for the high and low-traffic periods derived from [40]. More specifically for each t^{sd} we generate a new demand t_r^{sd} as follows:

$$t_r^{sd} = \max(\lceil \Delta \times (t^{sd} + \text{uniform}[-\lambda, \lambda] \times t^{sd}) \rceil, 0), \qquad (13)$$

where Δ is a scaling factor, and λ is a factor describing the level of randomness inserted into the traffic (influencing both spatial and temporal traffic distribution). It is important to note that as a result of this operation there is no guarantee that a traffic matrix with random perturbations will require the establishment of the same number of lightpaths in total as the one from which it originated from.

Technology parameters: We assume that all network nodes have full wavelength conversion capability, each fiber link (i, j, k) has a capacity of 80 wavelengths, OLAs are placed every 80 km, all OLAs are initially set to SM, and each OLA consumes 110 Watts [7] when in AM and a negligible amount of power when in SM. We do not consider the energy consumed by transponders and line cards since our proposed lifetime-aware strategies have no influence on their occupancies. Finally, we assume the same HW parameters AF_{ijkq}^{sleep} and χ_{ijkq} for all the OLAs in a link (i, j, k). Unless specified otherwise, the lifetime parameters have values

[4]The network design solution from [3] is based on the maximum value of the IP traffic measured in the period 01–31/07/2004 for the Abilene network [37, 38] and in the period 05/05/2005–04/06/2005 for the Géant network [38, 39]. Out of the three scaling factors used in [3], we choose the one leading to the sum of traffic originating and terminating at each node equal to 500 Gbps.

[5]Out of the three algorithms used in [40], this work is based on the results from Energy Watermark Algorithm (EWA) that uses the same traffic scaling parameter used in the network design phase [3].

$AF^{sleep}_{ijkq} = 0.2$ and $\chi_{ijkq} = 0.5$. With $AF^{sleep}_{ijkq} = 0.2$, the gain for putting an OLA into SM is relatively high (i.e., the lifetime is increased five times compared to the case in which the OLA is always kept in AM). However, the weight χ_{ijkq} multiplying the transitions between AM and SM tends to rapidly decrease the lifetime (i.e., four power cycles will bring to a maximum lifetime degradation equal to 50%). Although a detailed characterization of the HW parameters is out of scope of this work, we point out the importance of measuring such parameters in real devices. We plan to perform this task as future work.

B. Results

The performance of the proposed lifetime-aware strategies are assessed using a custom built event-driven simulator. The MILP models are created by the simulator and solved using Gurobi Optimizer [41]. A Debian Linux workstation with 2 Intel Xeon CPUs (6 cores per CPU) clocked at 2.2 GHz and with 32 GB of RAM is used for the simulations, and requires 2–120 seconds to solve any of the proposed MILP instances. At the beginning of an experiment (i.e., when solving the lightpath establishment problem for the first day), all OLAs are assumed to be in SM and a low period traffic matrix is considered first. When the MILP models presented in Section IV are solved, the resulting lightpath routing and wavelength assignment solution together with the information about the power state of each OLA are mapped into the network. This process is repeated in each traffic period for each one of the 15 days (i.e., 360 hours) considered in one experiment.

When using the set of traffic matrices based on real traffic measurements, only one 15-day long experiment is run for each of the proposed MILP models. On the other hand, when using the set of traffic matrices with random perturbations, multiple 15 days experiments are run to smooth out the effects of the random traffic. More specifically the results reported in the figures are the average over 30 different experiments and the error bars represent the confidence interval computed with a 95% confidence level. Finally, the values of the Δ and λ parameters are reported in the figure captions, when a set of traffic matrices with random perturbations is used.

In order to limit the overall complexity of the system we assume a centralized control architecture where a controller collects all the required information about the traffic and the operating conditions of the OLAs. This information is then used to select which devices should be in AM and which ones should be in SM. In addition, it can be noted that the proposed methodology requires only two power state transitions per day (at maximum). As a result, (1) the time required to put a device into SM (or vice-versa into AM) becomes almost negligible compared to the duration of each traffic period (minutes vs. several hours), and (2) the amount of control information distributed throughout the network is also contained.

LAF, LAF-EA, and LAF-TH are evaluated in terms of average AF and energy saving. At the end of each traffic period, the average AF is computed by averaging the AF value of all the OLAs in the network. On the other hand, the value of the energy saving is computed as the difference between the value of the energy consumption when all the OLAs in the network are always in AM and the value of the energy consumed by the set of OLAs in AM after applying the lifetime-aware strategy under exam. For benchmarking purposes the performance results of the proposed lifetime-aware strategies are compared with the results of the Energy-Aware (EA) ILP model presented in [42].

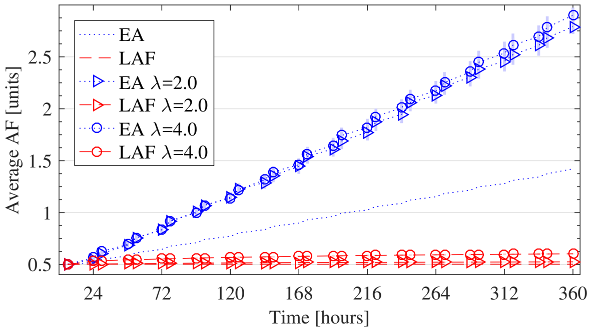
Table II presents the final performance results (i.e., after solving the high period traffic matrix of the 15th day) for the AF (i.e., in terms of minimum, average, and maximum) and the energy saving. The results refer to both the Abilene and Géant networks when the EA and LAF strategies are used to solve the multi-period lightpath establishment problem with the set of traffic matrices based on real traffic measurements. The EA strategy presents a high degradation of the value of the average and maximum AF in both network topologies when compared with the results obtained with the LAF strategy. On the other hand, the LAF strategy is able to achieve comparable if not identical energy saving performance as EA while, at the same time, being able to improve the average AF value by 65–69%. The value of the minimum AF is the same for both EA and LAF. This is because in both cases there is at least one OLA that is never put into AM (i.e., $AF^{sleep}_{ijkq} = 0.2$). In the case of LAF, the OLAs in the network do not experience any lifetime degradation (i.e., the maximum AF is equal to 1), while with EA there is at least one OLA that experiences a much worse maximum AF degradation, i.e., the maximum AF is in the order of 7.92.

TABLE II
FINAL RESULTS FOR EA AND LAF AFTER A 15-DAY PERIOD WITH A SET OF TRAFFIC MATRICES BASED ON REAL TRAFFIC MEASUREMENTS.

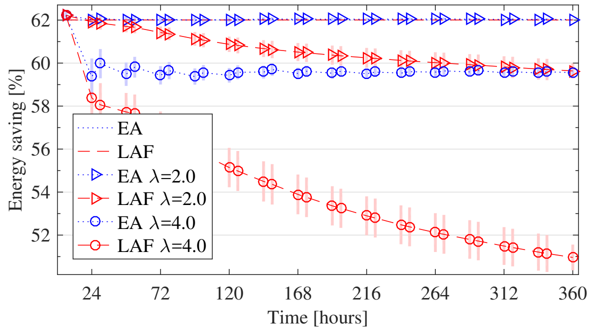
Network	**Strategy**	**Energy saving (%)**	**AF (min)**	**AF (avg)**	**AF (max)**
Abilene	EA	62.00	0.20	1.42	7.92
	LAF	62.00	0.20	0.50	1.00
Géant	EA	57.75	0.20	1.69	7.92
	LAF	57.50	0.20	0.53	1.00

Fig. 2 presents performance results for the EA and the LAF strategy when using the traffic matrices based on both real traffic measurements and the ones with random perturbations. Both network topologies are considered. For the random traffic generation we assume $\Delta = 1.0$ and λ equal to 2 and 4 for Abilene, and 2, 4, and 6 for Géant. This is done to assess the impact of traffic randomness on the device lifetime and energy saving performance. As it can be noticed from the figures, traffic randomness has a very limited impact on the average AF value in the case of LAF.

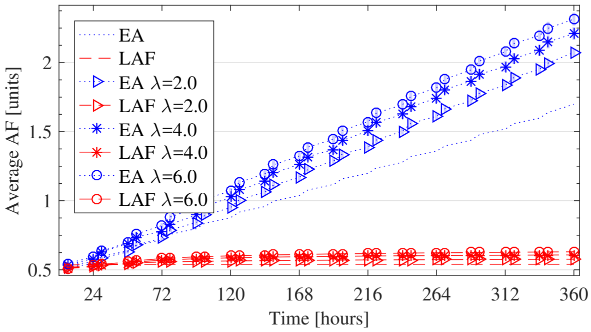
The impact of randomness on the energy saving performance is more tangible. In the Abilene network, we have a 62% energy saving for EA and LAF with traffic matrices derived from measurements and for EA with $\lambda = 2.0$. LAF with $\lambda = 4.0$ present energy saving that drops to around 51% at the end of the 15-day period. In the Géant network, traffic randomness allows EA to achieve higher energy saving. This is because with the introduction of randomness some node pairs in the network might be required to establish a lower number of lightpaths compared to the case of traffic without



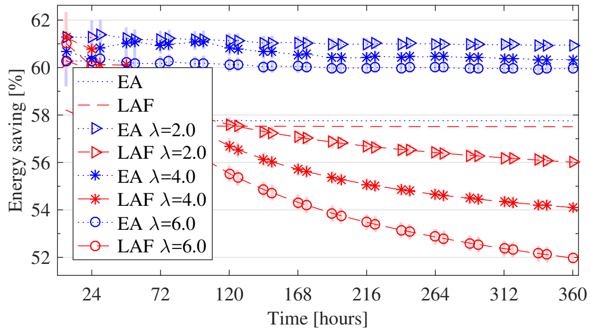
(a) Average AF over all OLAs for Abilene.



(b) Energy saving for Abilene.



(c) Average AF over all OLAs for Géant.



(d) Energy saving for Géant.

Fig. 2. Results for Abilene and Géant networks using EA and LAF strategies under fixed and random traffic (indicated with λ in the legends).

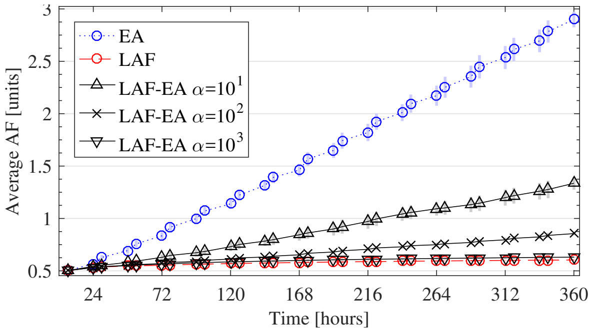
randomness. On the other hand, LAF presents lower energy saving performance with increasing time, since LAF tries to limit the number of AM-SM transitions, thus negatively impacting the energy saving performance.

The results for the LAF-EA strategy are presented in Fig. 3 together with the results of the EA and LAF strategies, provided in the figure for comparison purposes. Different values of the α parameter are also considered to better understand its impact on the energy and lifetime performance. In the case of the Abilene network, the LAF-EA strategy with $\alpha = 10^1$ presents similar energy saving as EA, but the lifetime degradation is half, compared to EA. This means that with LAF-EA it is possible to achieve very good energy saving performance and still have a low lifetime degradation. With $\alpha = 10^2$, the lifetime degradation is very close to LAF (only 0.3 higher), while the energy saving is only 1% less than EA at the end of the 15-day period. In summary, it is possible to conclude that with the α parameter it is possible to fine tune the performance of LAF-EA (i.e., give more priority to energy saving or, alternatively, to lower lifetime degradation), while still keeping a good general performance trade-off. Similar conclusions can be drawn for the case of the Géant network.

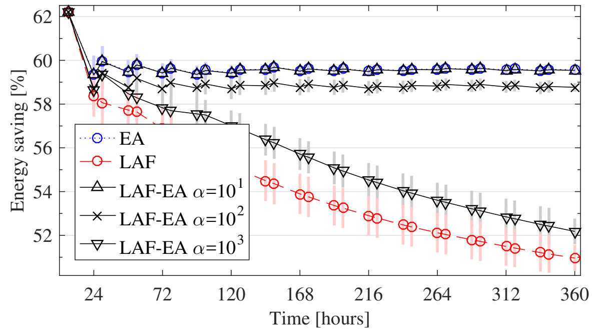
The results for the LAF-TH strategy are presented in Fig. 4. The figures relative to the average AF metric show that this strategy is effective at limiting the lifetime degradation and that the average value of AF is always kept below the given value of γ. This is because once the lifetime degradation threshold is reached, it is impossible to put an OLA into SM even when the OLA is not needed to route any traffic. Another interesting aspect to notice is the energy saving performance of LAF-TH. At the beginning of each experiment LAF-TH follows closely the energy saving performance of EA, then it starts dropping. This is again due to the fact that at the beginning of an experiment the AF value of the OLAs in the network is relatively low. As a result OLAs can be put into SM relatively frequently. On the other hand, the value of AF starts to increase as time passes by, and fewer and fewer OLAs can be put into SM, hence the drop in the energy saving performance.

Table III presents the final performance results (i.e., after solving the problem for the high-traffic period of the 15th day) for the AF (i.e., in terms of minimum, average, and maximum) and the energy saving. The results refer to both the Abilene and Géant network topologies when the strategies are used to solve the multi-period lightpath establishment problem with both the sets of traffic matrices based on real traffic measurements and the ones with random perturbations. When traffic randomness is added, it is assumed that $\Delta = 1$ while the value of λ is reported in the table. For LAF-TH we assume $\alpha = 10^1$ for all the experiments. The results in the table confirm the trends witnessed in all the plots presented so far. It is interesting to notice that in some cases the value of the maximum AF is higher than the threshold. This might happen when an OLA in SM reaches the threshold, but then it is later needed to route some traffic, i.e., it is put into AM to meet the traffic demand thus increasing its AF value beyond the threshold.

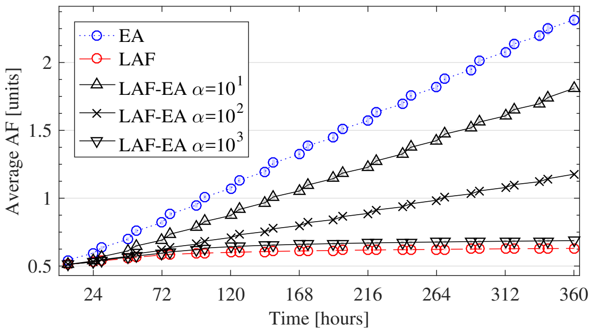
Table IV presents the average value of the lightpath length (AVG) after solving the problem for the Low-Traffic (LT) and the High-Traffic (HT) periods until the 15th day of our experiment. The results refer to both the Abilene and Géant network topologies when the proposed strategies are used to solve the multi-period lightpath establishment problem with both sets of traffic matrices, i.e., based on real traffic measurements with and without random perturbations. Even if



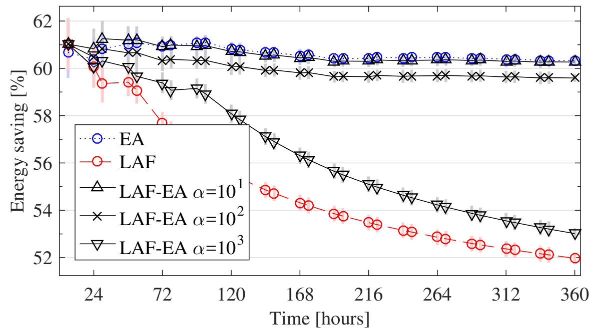
(a) Average AF over all OLAs for Abilene with λ = 4.0.



(b) Energy saving for Abilene with λ = 4.0.

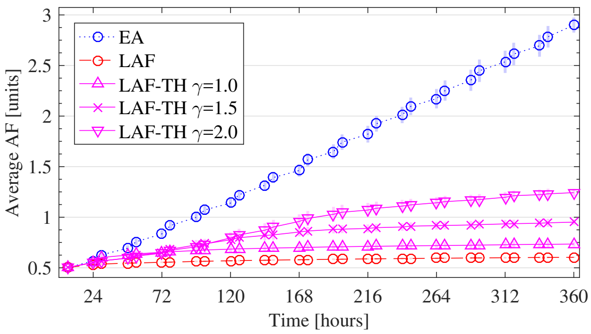


(c) Average AF over all OLAs for Géant with λ = 6.0.

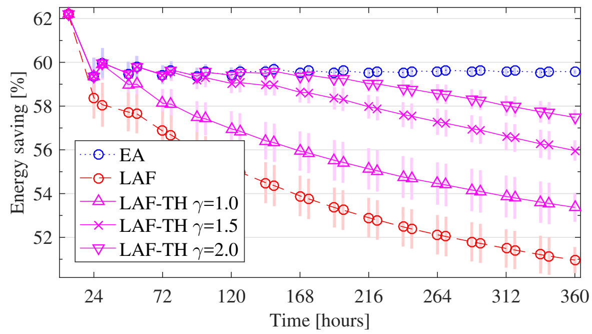


(d) Energy saving for Géant with λ = 6.0.

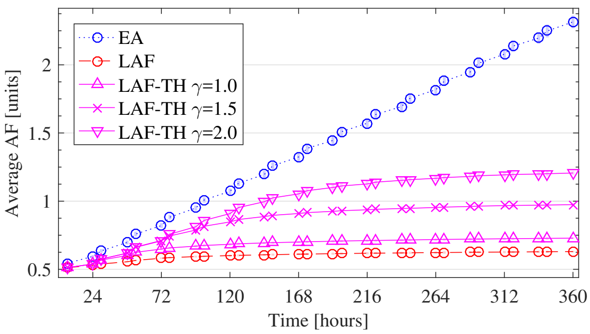
Fig. 3. Results for Abilene and Géant topologies using EA, LAF, and LAF-EA strategies under random traffic with Δ = 1.0.



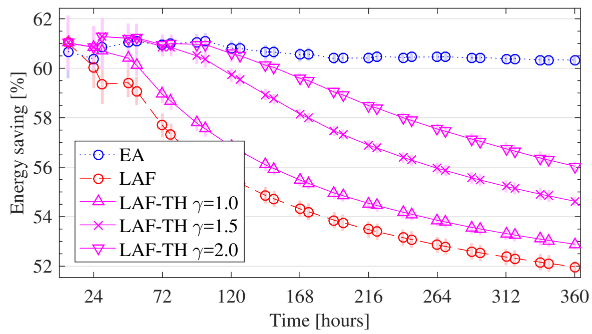
(a) Average AF over all OLAs for Abilene with λ = 4.0.



(b) Energy saving for Abilene with λ = 4.0.



(c) Average AF over all OLAs for Géant with λ = 6.0.



(d) Energy saving for Géant with λ = 6.0.

Fig. 4. Results for the Abilene and Géant networks using the EA, LAF, and LAF-TH strategies with α = 10^1 and γ as reported in the legend. Traffic has random perturbations with Δ = 1.0 and λ varying as indicated in each figure caption.

the proposed MILP models do not consider the lightpath length in their objective function, the table is helpful in understanding if the proposed policies used to control the frequency in which OLAs are put into SM might have a negative impact on the average path length, and consequently on the end-to-end latency experienced by some of the provisioned services.

TABLE III

FINAL RESULTS FOR EA, LAF, LAF-EA, AND LAF-TH AFTER A 15-DAY PERIOD (TRAFFIC MATRICES BASED ON REAL TRAFFIC MEASUREMENTS WITH AND WITHOUT RANDOM PERTURBATIONS).

	Strategy	**Energy Saving (%)**	**AF (min)**	**AF (avg)**	**AF (max)**
Abilene	EA	62.00	0.20	1.42	7.92
	LAF	62.00	0.20	0.50	1.00
	EA $\lambda = 2$	62.03	0.20	2.79	4.55
	LAF $\lambda = 2$	59.63	0.20	0.52	1.35
	EA $\lambda = 4$	59.56	0.20	2.89	5.17
	LAF $\lambda = 4$	51.27	0.20	0.60	1.44
	LAF-EA $\lambda = 4$, $\alpha = 10^1$	59.54	0.20	1.33	4.49
	LAF-EA $\lambda = 4$, $\alpha = 10^2$	58.57	0.20	0.88	4.48
	LAF-EA $\lambda = 4$, $\alpha = 10^3$	52.34	0.20	0.62	1.90
	LAF-TH $\lambda = 4$, $\gamma = 1.0$	53.47	0.20	0.76	1.46
	LAF-TH $\lambda = 4$, $\gamma = 1.5$	56.30	0.20	0.98	1.91
	LAF-TH $\lambda = 4$, $\gamma = 2.0$	57.58	0.20	1.23	2.36
Géant	EA	57.75	0.20	1.69	7.92
	LAF	57.50	0.20	0.53	1.00
	EA $\lambda = 2$	60.94	0.20	2.07	5.48
	LAF $\lambda = 2$	56.01	0.20	0.57	1.46
	EA $\lambda = 4$	60.33	0.20	2.24	5.49
	LAF $\lambda = 4$	54.10	0.20	0.60	1.51
	EA $\lambda = 6$	59.94	0.20	2.53	5.92
	LAF $\lambda = 6$	51.97	0.20	0.63	1.51
	LAF-EA $\lambda = 6$, $\alpha = 10^1$	60.26	0.20	1.80	5.18
	LAF-EA $\lambda = 6$, $\alpha = 10^2$	59.59	0.20	1.17	5.06
	LAF-EA $\lambda = 6$, $\alpha = 10^3$	53.01	0.20	0.68	2.04
	LAF-TH $\lambda = 6$, $\gamma = 1.0$	52.88	0.20	0.72	1.47
	LAF-TH $\lambda = 6$, $\gamma = 1.5$	54.62	0.20	0.97	1.94
	LAF-TH $\lambda = 6$, $\gamma = 2.0$	56.03	0.20	1.20	2.40

TABLE IV

AVERAGE LIGHTPATH LENGTH (AVG) IN THE LOW-TRAFFIC (LT) AND HIGH-TRAFFIC (HT) PERIOD FOR EA, LAF, LAF-EA, AND LAF-TH AFTER A 15-DAY PERIOD (TRAFFIC MATRICES BASED ON REAL TRAFFIC MEASUREMENTS WITH AND WITHOUT RANDOM PERTURBATIONS).

	Strategy	**AVG [km]**	**LT [km]**	**HT [km]**
Abilene	EA	4387	4492	4276
	LAF	4567	4687	4439
	EA $\lambda = 2$	3975	4284	3674
	LAF $\lambda = 2$	4188	4117	4203
	EA $\lambda = 4$	3284	3411	3163
	LAF $\lambda = 4$	3486	3450	3429
	LAF-EA $\lambda = 4$, $\alpha = 10^1$	4063	3725	4301
	LAF-EA $\lambda = 4$, $\alpha = 10^2$	4027	3789	4178
	LAF-EA $\lambda = 4$, $\alpha = 10^3$	3627	3552	3630
	LAF-TH $\lambda = 4$, $\gamma = 1.0$	3469	3359	3597
	LAF-TH $\lambda = 4$, $\gamma = 1.5$	3553	3576	3584
	LAF-TH $\lambda = 4$, $\gamma = 2.0$	3707	3700	3798
Géant	EA	7442	5633	9050
	LAF	5411	5561	5298
	EA $\lambda = 2$	8051	7880	8249
	LAF $\lambda = 2$	3692	3514	3739
	EA $\lambda = 4$	7454	7295	7637
	LAF $\lambda = 4$	3087	2951	3084
	EA $\lambda = 6$	6905	6758	7074
	LAF $\lambda = 6$	2754	2760	2757
	LAF-EA $\lambda = 6$, $\alpha = 10^1$	3448	3375	3598
	LAF-EA $\lambda = 6$, $\alpha = 10^2$	3158	3099	3210
	LAF-EA $\lambda = 6$, $\alpha = 10^3$	2813	2811	2878
	LAF-TH $\lambda = 6$, $\gamma = 1.0$	2705	2662	2756
	LAF-TH $\lambda = 6$, $\gamma = 1.5$	2867	2868	2868
	LAF-TH $\lambda = 6$, $\gamma = 2.0$	3027	2936	3073

The results reported in the table show that, in the case of the Géant network topology, this is never the case. However, when looking at the results from the Abilene network topology, the lifetime-aware approaches (i.e., LAF, LAF-EA, and LAF-TH) show a slight increase in the average lightpath length values compared to the EA case. On the other hand, the differences amount to only a few percent, and their impact on the end-to-end service latency can be considered negligible.

Fig. 5 shows the value of the final average AF after the 15-day period as a function of the variations of HW parameters AF^{sleep}_{ijkq} and χ_{ijkq}. It can be noticed that when the value of AF^{sleep}_{ijkq} is increased, the gain of putting OLAs into SM is reduced and the value of the average AF tends to increase (except for the case when the threshold $\gamma = 1.5$ is reached). At the same time, when χ_{ijkq} is increased, the impact of power state transitions is higher. While the EA tends to notably increase the AF when the HW parameters are increased, our proposed lifetime-aware strategies are able to limit this lifetime degradation. The results in the figure refer to the Abilene network. Similar results have been obtained also for the Géant network, but are not reported here due to the lack of space.

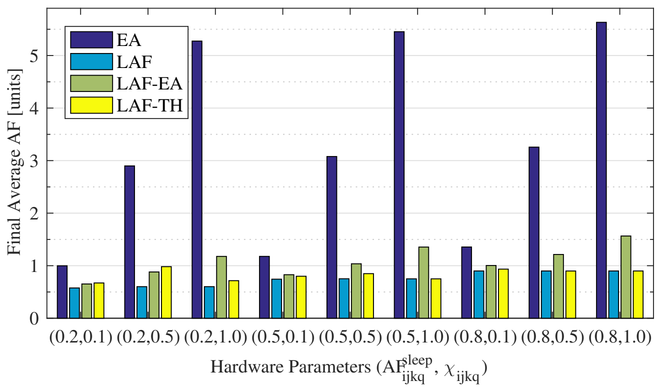


Fig. 5. Results for the Abilene network with different HW parameters values and traffic randomness obtained with $\Delta = 1.0$ and $\lambda = 4.0$. For LAF-EA and LAF-TH we assume $\alpha = 10^2$ and for LAF-TH $\gamma = 1.5$.

VI. SUMMARY AND FUTURE WORK

The paper studies the problem of how to manage the OLA lifetime in an optical network where unused devices can be put into SM. First we have detailed the AF metric, which is used to compute the lifetime increase/decrease w.r.t. a reference case (i.e., the OLA is always kept in AM). We have then proposed three different MILP formulations (namely LAF, LAF-EA, and LAF-TH) to optimize the weighted sum of the energy consumption and the AF values. We have compared the proposed models with a classical EA formulation, which instead does not consider its impact on the AF. Results, obtained by imposing temporal and spatial variations of traffic over different network scenarios, show that LAF, LAF-EA, and LAF-TH are able to efficiently trade between the increase in the AF and the energy consumed. As next steps, we plan to measure the physical parameters of the AF model with real devices, to develop heuristic solutions for the proposed MILP formulations, to study the economical impact of AF degradation, and to consider device lifetime in green elastic optical networks. As a final note we would like to highlight that it is also of mandatory importance to experimentally validate the obtained results with real network settings, a task that we plan to carry out as soon as we will have access to a proper testbed facility.

Acknowledgment

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