Joint Optimization of Failure Management Costs, Electricity Costs, and Operator Revenue in Optical Core Networks

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***Abstract*—We focus on the problem of maximizing profitability in an optical core network by acting on the power states of Optical Line Amplifiers (OLAs) and Line Cards (LCs) operating under varying traffic. Specifically, the profitability metric considered in this work takes into account the electricity costs of OLAs and LCs, the failure management costs derived from the application of power states to the network devices, and the operator revenue. After proving that all terms of the considered profitability function are deeply inter-correlated, we formulate the optimization problem of maximizing the network profitability in an optical core network with multi-period traffic. By solving the proposed formulation on a realistic scenario, we show that it is possible to wisely trade between the considered costs and revenue, and achieve higher network profitability than in the case in which the single terms are considered in isolation, e.g., only electricity consumption or only Failure Management Costs (FMC).**

***Index Terms*—Optical core network operation; optimization, operational expenditure; operator profit; electricity costs; failure management costs; operator revenue.**

I. INTRODUCTION

CORE networks provide high data rates to exchange information from/to users connected via access networks. Thanks to the exploitation of the 5G technology [1], the bandwidth required from users is expected to notably grow in the near future. In addition, a large amount of traffic is also exchanged among distributed Data Centers (DCs) [2]. Finally, Machine-to-Machine (M2M) communication will also contribute to this traffic growth [3] thanks to the diffusion of the Internet of Things (IoT) paradigm [4].

In this context, core network operators face several challenges. First, it is of capital importance to serve the traffic originating from different access networks, that in turn present an increasing elasticity of traffic demands [5]. Second, a reduction in the Operational Expenditures (OpEx) incurred by the network infrastructure is also imperative. To tackle the latter challenge, operators and research community have targeted the reduction of the power consumption of the network devices, starting from the seminal work of Gupta *et al.* [6].

Two of the straightforward approaches to reduce power consumption in a core network are: *(i)* install more energy-efficient devices, and/or *(ii)* manage the power states of the network devices during the operation phase. The first approach incurs non-negligible Capital Expenditures (CapEx) for an operator in order to buy and install new devices [7], and is not covered in this work. Additionally, unplanned upgrade of devices are in contrast with the operator goal to maximize the Return of Investment (RoI) of its equipment. Therefore, managing the power states of network devices becomes more attractive, and can be realized through the exploitation of Sleep Mode (SM) state. The SM constitutes a promising alternative to save energy, and consequently to reduce the Electricity Costs (EC) paid by an operator [8, 9]. The topic of managing the energy consumption of a core network during its operation has been deeply investigated by different works (see e.g., [10–12] for comprehensive surveys).

Although the benefits of SM in terms of reduction of EC are clear and well investigated, the full implications of this approach on core network devices are still an open issue. Specifically, the use of SM has an impact on the lifetime of the devices, and consequently on the Failure Management Costs (FMC) paid by the operator [13]. For instance, when the device changes its power state from Active Mode (AM) to SM or vice-versa, the probability to activate thermal crack effects on the components of a network device is increased (see e.g., [14, 15] for the case of chip components). As a result, the device lifetime tends to decrease when power state changes are applied across time compared to the case in which the device is always kept active. Therefore, the associated FMC, i.e., the ones paid by the operator in order to repair a device or to replace it with a new one, will increase. In the worst case the FMC paid by the operator will completely surpass the electricity saving derived from the application of SM-based solutions [13].

In this scenario, several questions arise, such as: Is it possible to jointly take into account the EC, the FMC, and the operator revenue from clients in a core network? What is the impact of these terms on the network profitability? How do different equipment types impact the FMC and EC? How to properly set up charging schemes to clients in order to balance the costs derived from electricity and from failure management operations? We answer these questions by focusing on an optical core network, in which Optical Line Amplifiers (OLAs) and Line Cards (LCs) are able to exploit a SM state. The closest paper to our work is [16], in which the authors focus on the joint optimization of the lifetime and of the power consumption in an optical core network. However, neither the

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effective costs paid by the operator nor the operator revenue related to the establishment of a new service is considered there. In addition, the work in [16] only focuses on OLAs and it does not consider other devices, such as LCs, which may heavily impact both failure management and energy costs. In this work we go five steps further by:

- taking into account both LCs and OLAs;
- defining a model for the EC, the FMC, and the operator revenue derived from the application of different power states to LCs and OLAs;
- jointly targeting the costs and revenue in the objective function of the proposed Profitability Formulation (PF);
- considering the impact of varying the traffic demands from clients for the operator revenue;
- presenting a methodology to compute the Energy-Maintenance (EM) break-even point, i.e., the point where the revenue is able to balance the energy and failure management costs.

We believe that all these points are of fundamental importance to understand the interplay of the different costs and revenue experienced by the operator when SM states are applied to the network devices. Moreover, our work will pave the way to the definition of efficient strategies in order to manage the network profitability. For example, the presented framework could be potentially integrated also with other costs/revenue incurred by the operator (e.g., site renting costs, regular failure management operations, impact of large events introducing spikes in the traffic demands), which can be easily added in the total profitability function.

The rest of the paper is organized as follows. An overview of the related work is presented in Section II. Section III defines the problem targeted in this paper, and reports the considered models in terms of costs and revenue. An illustrative use case example is presented in Section IV. The optimal formulation of the problem is detailed in Section V. Section VI provides a description of the considered simulation scenario and details the setting of the parameters. The performance assessment of the considered problem is reported in Section VII. Finally, Section VIII concludes our work and presents some ideas for future studies.

II. RELATED WORK

We review works that tackle energy-efficient operation of optical networks, and distinguish between: *(i)* Electricity Costs (EC), *(ii)* Failure Management Costs (FMC), and/or *(iii)* profits of a network operator. Moreover, we point out that works targeting other layers (such as the Internet Protocol (IP) one [17]), network design approaches (i.e., installing new devices as surveyed in [12]) minimizing Capital Expenditures (CapEx) or other costs (such as power or port costs of [18–20]) are orthogonal to this paper.

Electricity Costs: The authors of [21, 22] target the minimization of the EC in an optical Wavelength Division Multiplexing (WDM) network under the assumption of time-varying electricity prices for nodes located in different time zones. They formulate a Mixed-Integer Linear Programming (MILP) for the Routing and Wavelength Assignment (RWA) problem and call it RWA-Bill. RWA-Bill is compared with RWA-Energy (which targets the minimization of energy consumption), and a classical RWA, where the minimization of the number of active wavelengths in the network is targeted. Results are expressed in hourly EC versus time of a day [21], and in normalized EC (with respect to conventional RWA) versus number of connection requests [22]. Neither operator revenue nor FMC are taken into account in [21, 22], and profitability is not the main target.

The joint optimization of power, EC, and delay in IP-over-WDM networks is studied in [23]. The authors formulate the problem as a MILP model and evaluate it in terms of non-renewable power consumption, EC, and propagation delay in the 14-node NSFnet network. Moreover, real-time energy-price-aware routing for IP-over-WDM networks is proposed in [24]. The proposed Least Dollar Cost Path (LDCP) routing algorithm is evaluated on the NSFnet topology using (among others) LDCP relative EC improvement and EC per successful request as evaluation metrics. The work [24] is extended in [25] for optical data center networks. Real-time energy-price-aware anycast RWA is tackled in the form of proposed Least Dollar Path (LDP) algorithm in [25]. Again, these works do not consider the impact of power state changes on the FMC and the revenue from clients, which may significantly influence the network profitability.

The idea of cutting EC is pursued also in [26]. The authors of this work propose an analytical model and consider various methods for saving energy using strategies (such as dynamic power scaling and smart standby) at the data-plane and at the control plane. They also propose an analytical energy profile model for different network segments, i.e., access, core, transport, and metro. This work is fundamentally different from ours due to its scope and methodology. FMC and network profits are not considered either.

Finally, there are several works tackling EC in the context of time-of-use pricing. Specially, operation costs of cloud services in an Optical Transport Network (OTN) are studied in [27]. Moreover, cost-efficient live Virtual Machine (VM) migration based on varying EC is considered in [28]. In addition, management of storage of solar (renewable) energy is the contribution of [29]. However, the impact on the other terms of the operator profitability, such as the FMC and the revenues from clients, are not taken into account.

Failure Management Costs: Energy saving requires dynamic switching of power state of network devices. This can influence their lifetime and hence induce extra FMC. Our previous works [30, 31] tackle this effect without taking EC into account. A function of monetary energy saving and reparation costs, called maximum allowable lifetime increase, is analyzed in [13] for optical and cellular devices. Minimization of a weighted sum of lifetime decrease and power consumption increase of all Optical Line Amplifiers (OLAs) in the network is targeted in [16]. Neither [13] nor [16] considers the revenue deriving from clients charged for their established LightPath (LP) services or the impact on the network profitability.

Network Profits: Focusing on the network profits achieved from a network subject to energy-efficient operation of the devices, the closest work to this one is [32], in which authors propose a heuristic to balance between the costs and the revenues in a cellular network. We go three steps further in this work compared to [32] by:

- focusing on an optical network scenario;
- optimally formulating the problem of maximizing the network profitability in an optical network;
- defining a new methodology to compute the minimum price that has to be charged to clients in order to balance the operator costs.

III. COSTS AND REVENUE MODELS

Our problem targets the maximization of the operator profitability through the optimization of the Failure Management Costs (FMC), the Electricity Costs (EC), and the operator revenue. We denote as operator profit the amount of money coming from the revenue (i.e., by charging clients) minus the FMC and EC. Our work is tailored to the network operation phase, where network devices are subject to periodical reconfigurations, in order to maximize the profitability while satisfying the traffic demands. The traffic varies with a day-night trend, where a time slot determines the amount of time between two consecutive traffic variations. Therefore, our solution aims at optimizing the network profitability by properly setting the power states of the network devices across the set of time slots. The output of the model is the network configuration for each time slot, i.e., which LightPaths (LPs) to establish, which route should each LP follow, and which devices to put into Sleep Mode (SM).

Before going into the details of the optimization problem, we first present the model used to compute the profitability by considering a generic single device serving a set of clients. The following subsections detail how the terms of the network profitability are computed.

A. Failure Management Costs

We first consider the costs incurred by the operator when the device has to be repaired or replaced as a consequence of a failure event triggered by the application of the different power states. In order to estimate such FMC, we need first to estimate the current lifetime of the device. Specifically, we follow the methodology proposed in [16], in which a metric, called (lifetime) Acceleration Factor (AF), is introduced. The AF is defined as the mean lifetime of the device under consideration ($\gamma^{tot}[1/h]$), normalized by the mean lifetime of the device when it is always kept in Active Mode (AM) ($\gamma^{on}[1/h]$):

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

where $\theta[h]$ is the amount of time spent by the device in SM (from the beginning of the observation up to current time slot), $\Delta_t[h]$ is the total amount of time up to the current time slot, c is the number of power state changes experienced by the device (from SM to AM, or vice-versa) from the beginning of the observation up the current time slot, and AF^{sleep} and χ are two HardWare (HW) parameters that depend on the components used to build the device.

Intuitively, an AF larger than 1 is observed when the lifetime of the device is reduced compared to the case in which the device is always kept in AM. This situation occurs when different power cycles (i.e., transitions between SM and AM) are performed, thus increasing the last term of (1).

The FMC $C_M[USD]$ for a generic device during a certain time slot is then defined as:

$$C_M = C_r \cdot MTTR \cdot \delta_t \cdot \gamma^{on} \cdot AF, \tag{2}$$

where $C_r[USD/h]$ is the hourly reparation crew cost for a device, $MTTR[h]$ is the value of the mean time to repair of the device, $\delta_t[h]$ is the time slot duration, and $\gamma^{on}[1/h]$ is the lifetime of the device when always kept in AM, AF is the acceleration factor as defined in (1).

B. Electricity Costs (EC)

In the following, we compute the costs to keep a generic device powered on. Specifically, the EC $C_E[USD]$ for a given device and a time slot duration of $\delta_t[h]$ is given by:

$$C_E = P \cdot C_{Wh} \cdot \delta_t \cdot x, \tag{3}$$

where $P[W]$ is the power of the device, $C_{Wh}[USD/Wh]$ is the EC per Watt-hour, and $x \in \{0, 1\}$ is its power state assuming value 1 if in AM or 0 if in SM during the current time slot. [1]

C. Operator Revenue

Finally, we provide a model to compute the operator revenue derived from the application of charges to clients. In our work, the term “client” refers to an entity using the core network, which can be another service provider owning an access network, or a cloud service provider serving a set of aggregated customers. We focus on LP requests from clients, and each LP established by the operator generates a revenue of $U^{lp}[USD/h]$ throughout its duration. The revenue $U_{sd}[USD]$ of all LPs established over a generic link connecting node s with node d of the network operator for a given period of time $\delta_t[h]$ is defined as:

$$U_{sd} = U^{lp} \cdot \delta_t \cdot r_{sd}, \tag{4}$$

where r_{sd} is the number of LPs established between nodes s and d. Revenue from all the lightpaths established in the network (between all node pairs) is denoted as U. With this model, the more LPs are established, the higher revenue is achieved by the operator.

D. Interactions Among the Models

Intuitively, the presented models are all interdependent. Let us assume the case in which the device is put from AM into SM at a given time slot. In this case, the total amount of time θ and the number of power state changes c are increased in (1), thus triggering a variation also on the network FMC of (2). At the same time, the term x of (3) is set to zero, thus leading to zero EC for the current time slot. Finally, the LPs that can

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[1] We assume that the power consumption of the device in SM is negligible w.r.t. the AM.

TABLE I
LP REQUESTS VS. TIME SLOT TS.

LP Requests ($B-C$)	TS_1	TS_2	TS_3
Minimum	1	2	1
Maximum	2	4	2

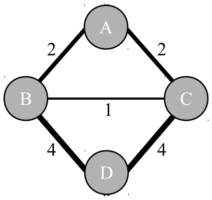


Fig. 1. Topology used for the illustrative case example. Numbers represent the link capacity in terms of LightPaths (LPs).

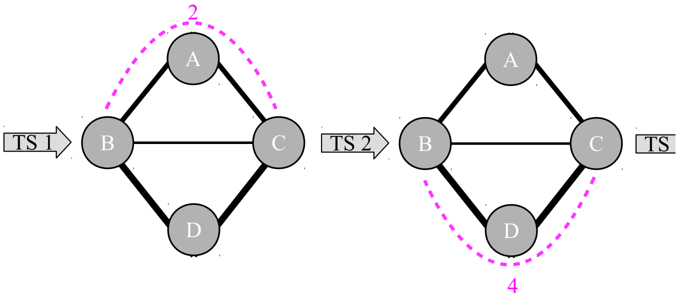
be established will also constrain the number of powered on resources according to (4). Eventually, when the set of devices in SM in a core network is increased, the traffic from clients is concentrated on few devices, which tends to increase their utilization. As a result, the goal of this work is to maximize the network profitability for the operator, which is defined as:

$$\max\left(U - C_M - C_E\right). \qquad (5)$$

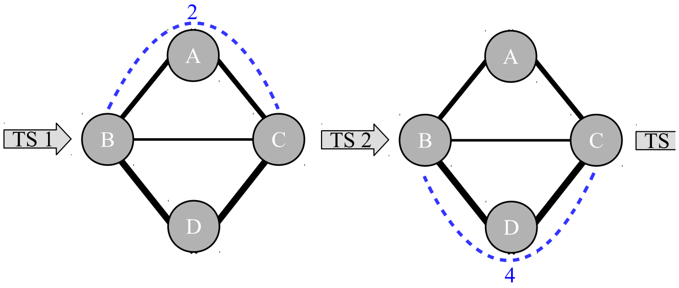
IV. ILLUSTRATIVE CASE EXAMPLE

We present a case study in order to better understand the impact of different strategies on the network profitability. We consider a Profitability-Aware (PA) strategy, which tends to maximize the network profitability, i.e., the focus of this work. We compare the PA strategy with an Energy-Aware (EA) solution that targets the maximization of the number of devices in Sleep Mode (SM) over time, i.e., maximize the energy saving. Additionally, we consider also a Lifetime-Aware (LA) strategy, which aims at maximization of the lifetime, i.e., by increasing the amount of time each device spends in SM and limiting the number of state transitions. We assume that the time is divided in time slots. For each time slot, a minimum and a maximum amount of LightPath (LP) requests between each source and each destination can be established. Each strategy then selects the set of devices in SM and in Active Mode (AM) for each time slot.

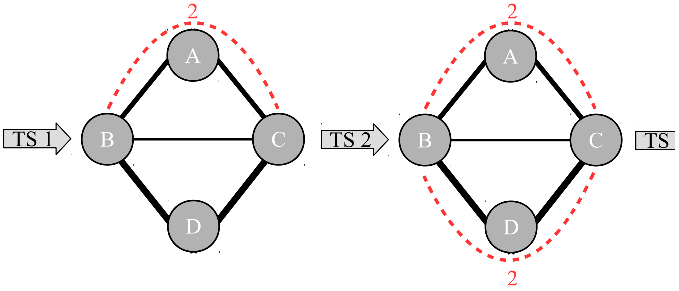
We use a network topology composed of four nodes. Fig. 1 illustrates the considered topology, as well as the capacity for each link expressed in terms of maximum number of LPs that can be carried by the link. The same number of Optical Line Amplifiers (OLAs) is assumed on each link. In this scenario, we assume that LPs need to be established between B and C. Table I reports the minimum and the maximum LP requests across three time slots. We then assume that the power states of the links in the topology can be varied over time. In addition, we provide an exemplary setting of the input parameters, which is reported as follows: $\Delta_t = 3$ [h], $AF^{sleep} = 0.5$ [units], $\chi = 1$ [1/h], $\delta_t = 1$ [h], $C_r = 500$ [USD], $\gamma^{on} = 1/500$ [1/h], $MTTR = 1$ [h], $P_{AB} = 1$ [kW], $P_{BC} = 1$ [kW], $P_{AC} = 0.5$ [kW], $P_{BD} = 2$ [kW], $P_{CD} = 2$ [kW], $C_{Wh} = 0.2$ [USD/kWh], $U^{lp} = 1$ [USD/h]. We point out that the realistic setting for all the input parameters, tailored to a more complex scenario and to realistic physical devices (i.e., OLAs and Line Cards (LCs)), is detailed in Section VI.



(a) PA strategy with elastic traffic matrices.



(b) EA strategy with traffic matrices chosen by the PA strategy.



(c) LA strategy with traffic matrices chosen by the PA strategy.

Fig. 2. A four-node network over three time periods using three operation strategies (PA, EA, and LA). Solid lines indicate physical links. Dashed lines indicate LPs and their routing over the physical topology. Numbers indicate the number of served LP requests. The links in SM are the ones without LPs traversing them.

Fig. 2 reports the evolution of the links power states and the amount of traffic routed in the network over the three time slots, by considering the three different strategies. Specifically, the dashed lines indicate LPs and their routing over the physical topology. Moreover, the number above each dashed line indicates the number of served LP requests. In addition, links carrying LPs are powered on, while the ones with no LPs are in SM. In this scenario, the proposed PA strategy wisely adapts the power state of the devices as well as routing of LPs to trade between costs and revenue (Fig. 2a). More in depth, PA is able to establish the maximum number of LPs that corresponds to the highest operator revenue. At the same time, the strategy is able to *(i)* limit the number of power state transitions (e.g., no transition from time slot $TS2$ to $TS3$ in Fig. 2a is triggered), and *(ii)* increase the amount of time spent in SM by some devices (e.g., links A–B and A–C in the time slots $TS2$ and $TS3$ in Fig. 2a).

TABLE II
Illustrative Case Example – Summary Of Metrics Including Failure Management Costs (FMC) and Electricity Costs (EC) After the Third Time Period.

Strategy	Total # of power state changes	Total amount of time in SM [h]	Total # of served LP requests	EC [USD]	FMC [USD]	Revenue [USD]	Profitability [USD]
PA	4	9	8	2	1.5	8	4.5
EA	8	9	8	1.6	2.3	8	4.1
LA	2	5	8	2.8	1.23	8	3.97

Figs. 2b and 2c show the network operated by the EA strategy and the LA strategy, respectively under the same traffic as the one chosen by the PA strategy (i.e., the maximum traffic – the EA and LA strategies are designed to take the number of LP requests as input parameters), in order to perform a fair comparison. The EA strategy (Fig. 2b) imposes to minimize the number of active devices, thus introducing a large number of power state variations, and consequently increasing the FMC. On the other hand, the LA strategy (Fig. 2c) tends to minimize the impact on the FMC, by limiting the number of power state transitions. However, this strategy may lead to higher EC compared to EA. In addition, both LA and EA do not consider the operator revenue impact on the network profitability.

Table II reports the evaluation metrics collected at the end of the considered time period. All the three strategies achieve the same operator revenue (8 LP requests served over the three time slots). However, Profitability Formulation (PF) achieves the highest profitability, being able to trade between EC, FMC, and operator revenue.

V. Optimal Profitability Formulation

We extend the models proposed in Section III to the physical devices of an optical network, i.e., Optical Line Amplifiers (OLAs) and Line Cards (LCs), with the goal of maximizing the network profitability for the operator. In the rest of the paper, we denote the optimization model we propose as Profitability Formulation (PF). We first report the main assumptions and the input parameters of PF. We then report the set of constraints. Finally, we detail the overall formulation.

A. Main Assumptions and Input Parameters

The PF model maximizes the profitability in a network subject to periodical reconfigurations at different time slots. For each time slot a traffic matrix has to be accommodated in the network. Each entry of the traffic matrix, denoted by a source/target node pair, has two values: *(i)* the minimum (min) number of LightPaths (LPs) r_{sd}^{min} to be established between the node pairs to guarantee an acceptable level of QoS to the clients and; *(ii)* the maximum (max) number of LPs r_{sd}^{max} to be established between the node pairs to achieve a maximum level of QoS. Our model always guarantees at least the first condition, while the number of LPs is eventually increased up to r_{sd}^{max}, if the network profitability is improved. Moreover, the problem is solved for each time period (traffic matrix) requiring as input the power state of the devices at previous time slot, the current traffic matrix, and the time slot duration.

We target two types of devices in our work, namely OLAs and LCs. OLAs are present in a relatively high number in optical networks. They are installed along the fiber links and their number is determined by the length of the fiber links. On the other hand, LCs are installed at the network nodes, usually in a number determined by the amount of traffic flowing from/to the network nodes. The two types of devices have different Mean Time To Repair (MTTR), lifetime, and power consumption features. For each type of device, we assume the same power consumption model, and the same HardWare (HW) parameters (i.e., AF^{sleep} and χ). In addition, all the nodes are capable of full wavelength conversion, i.e., we do not consider wavelength continuity constraint in our model.[2] Finally, Table III reports the main notation of the problem that is going to be introduced in the next subsections. In the following, we introduce the different sets of constraints, and then we report the overall formulation.

B. Flow Conservation and Power State Constraints

The routing of the traffic and the control of the power states are imposed through constraints (6)-(10).

$$\sum_{j=1}^{|N|}\sum_{k=1}^{|K_{ij}|} f_{ijk}^{sd} - \sum_{j=1}^{|N|}\sum_{k=1}^{|K_{ji}|} f_{jik}^{sd} = \begin{cases} r_{sd} & , i = s \\ -r_{sd} & , i = d \\ 0 & , i \neq s, d \end{cases}, \quad \forall s, d, i \in N. \tag{6}$$

$$r_{sd}^{min} \leq r_{sd} \leq r_{sd}^{max}, \quad \forall s, d \in N. \tag{7}$$

$$f_{ijk} = \sum_{s=1}^{|N|}\sum_{d=1}^{|N|} f_{ijk}^{sd}, \tag{8}$$

$$f_{ijk} \leq W_{ijk} \cdot x_{ijk}^{ola}, \quad \forall (i,j) \in E, \forall k \in K_{ij}. \tag{9}$$

$$\begin{cases} \sum_{\phi=1}^{|\Phi_n|} x_{n\phi}^{lc} \geq \sum_{s=1}^{|N|} r_{sn} \\ \sum_{\phi=1}^{|\Phi_n|} x_{n\phi}^{lc} \geq \sum_{s=1}^{|N|} r_{ns} \end{cases}, \quad \forall n \in N. \tag{10}$$

Specifically, (6) ensures the traffic conservation flow for all the demands. (7) bounds the number of established LPs between minimum and maximum number of LPs, according to the traffic matrix. (8) computes the total number of LPs traversing fiber link k between nodes i and j, i.e., the number of wavelengths used on the link. (9) ensures that each fiber link (i, j, k) must not be traversed by more LPs than its number of wavelengths, as well as define if such a fiber link needs to be in AM or not by setting the variable x_{ijk}^{ola}. Finally, (10) ensures that the number of LCs in AM on each node in the network is greater or equal to the number of LP requests established from/to such network node.

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[2] The costs of electricity and failure management of wavelength converters are constant assuming that they are not dynamically switched between Active Mode (AM) and Sleep Mode (SM) and thus do not influence the outcome of this study.

TABLE III
MILP MODEL MAIN NOTATION.

	Symbol	Unit	Description
Input Parameters	N	-	Set of nodes
	E	-	Set of physical links, each link $(i, j) \in E$ from node $i \in N$ to node $j \in N$
	K_{ij}	-	Set of fiber links on the physical link $(i, j) \in E$
	O_{ijk}	-	Set of OLAs installed in fiber link (i, j, k), $(i, j) \in E, k \in K_{ij}$
	M	-	Set of traffic matrices, each $m \in M$ representing the traffic matrix for one time period
	T	-	Set of traffic periods, each $t \in T$ of duration $\delta_t[h]$ representing the number of hours
	Δ_t	[h]	total duration of simulation experiment up to current traffic period
	R	-	Set of LP requests during the current time period, each LP request $r_{sd} \in R$ with $r_{sd}^{min} \in R$ and $r_{sd}^{max} \in R$ representing, respectively, the minimum and maximum number of LPs to be established between the source node $s \in N$ and the destination node $d \in N$
	Φ	-	Set of LCs installed in the network, each one (n, ϕ) representing the LC $\phi \in \Phi$ installed on the node $n \in N$
	Φ_n	-	Set of LCs installed at node $n \in N$, $\Phi_n \subseteq \Phi$
	W_{ijk}	[unit]	Total number of wavelengths installed on fiber link (i, j, k)
	C_{Wh}	[USD/Wh]	Electricity Costs (EC) per Watt-hour
	U^{lp}	[USD/h]	Revenue brought to operator for establishing a LP over an hour
	σ	[unit]	Overprovisioning parameter used to calculate the maximum number of LP requests r_{sd}^{max} (28)
	α	[unit]	A constant big number greater than any AF_{ijkq}^{ola}, and greater than any $AF_{n\phi}^{lc}$
	C_r^{ola}	[USD/h]	Hourly reparation cost for each OLA installed in the network
	P^{ola}	[Watt]	Power consumption of each OLA installed in the network
	γ_{ola}^{on}	[1/h]	Failure rate of each OLA installed in the network
	$MTTR^{ola}$	[h]	Mean Time To Repair an OLA
	χ^{ola}	[1/h]	HW parameter accounting for the AF increase due to power state transitions for any OLA
	X_{ijk}^{ola}	[unit]	1 if fiber link (i, j, k) was in AM during the previous time period, and 0 otherwise
	C_{ijkq}^{ola}	[unit]	Total number of power state transitions of OLA q on fiber link (i, j, k) up to the previous time period
	Θ_{ijkq}^{ola}	[h]	Total time spent by OLA q on fiber link (i, j, k) in SM up to the previous time period
	AF_{ola}^{sleep}	[unit]	AF when an OLA in the network is in SM
	ρ^{ola}	[unit]	The AF threshold used to limit lifetime degradation of each OLA
	C_r^{lc}	[USD/h]	Hourly reparation cost for each LC installed in the network
	P^{lc}	[Watt]	Power consumption of each LC installed in the network
	γ_{lc}^{on}	[1/h]	Failure rate of each LC installed in the network
	$MTTR^{lc}$	[h]	Mean Time To Repair a LC
	χ^{lc}	[1/h]	HW parameter accounting for the AF increase due to power state transitions for any LC
	$X_{n\phi}^{lc}$	[unit]	1 if LC (n, ϕ) was in AM during the previous time period, and 0 otherwise
	$C_{n\phi}^{lc}$	[unit]	Total number of power state transitions of LC (n, ϕ) up to the previous time period
	$\Theta_{n\phi}^{lc}$	[h]	Total time spent by LC (n, ϕ) in SM up to the previous time period
	AF_{lc}^{sleep}	[unit]	AF when a LC in the network is in SM
	ρ^{lc}	[unit]	The AF threshold used to limit lifetime degradation of each LC
Variables	r_{sd}	[unit]	Number of LP requests actually to be established from node s to node d $(s, d \in N)$ for current time period
	f_{ijk}^{sd}	[unit]	Number of used wavelengths for the LPs requested between nodes s and d traversing fiber link (i, j, k)
	f_{ijk}	[unit]	Total number of used wavelengths on fiber link (i, j, k)
	x_{ijk}^{ola}	[unit]	1 if fiber link (i, j, k) is in AM during the current time period, 0 otherwise
	z_{ijk}^{ola}	[unit]	1 if fiber link (i, j, k) changes power state from the previous time period to the current time period, 0 otherwise
	c_{ijkq}^{ola}	[unit]	Total number of power state transitions of OLA q on fiber link (i, j, k) up to the current time period
	θ_{ijkq}^{ola}	[h]	Total time in SM for OLA q on fiber link (i, j, k) up to the current time period
	AF_{ijkq}^{ola}	[unit]	Total Acceleration Factor (AF) of OLA q on fiber link (i, j, k) up to the current time period
	h_{ijkq}^{ola}	[unit]	1 if the AF of OLA (i, j, k, q) violates the threshold ρ^{ola}, 0 otherwise
	$x_{n\phi}^{lc}$	[unit]	1 if LC (n, ϕ) is in AM during the current time period, 0 otherwise
	$z_{n\phi}^{lc}$	[unit]	1 if LC (n, ϕ) changes power state from the previous traffic period to the current time period, 0 otherwise
	$c_{n\phi}^{lc}$	[unit]	Total number of power state transitions of LC (n, ϕ) up to the current time period
	$\theta_{n\phi}^{lc}$	[h]	Total time in SM for LC (n, ϕ) up to the current time period
	$AF_{n\phi}^{lc}$	[unit]	Total AF of LC (n, ϕ) up to the current time period
	$h_{n\phi}^{lc}$	[unit]	1 if the AF of LC (n, ϕ) violates the threshold ρ^{lc}, 0 otherwise

C. AF Computation for OLAs and LCs

The constraints (11)–(14) compute the AF for the OLAs. We recall that the AF is then used for the computation of the Failure Management Costs (FMC).

$$\begin{cases} x_{ijk}^{ola} - X_{ijk}^{ola} & \leq z_{ijk}^{ola} \\ X_{ijk}^{ola} - x_{ijk}^{ola} & \leq z_{ijk}^{ola} \end{cases}, \quad \forall (i, j) \in E, \forall k \in K_{ij}. \tag{11}$$

$$c_{ijkq}^{ola} = C_{ijkq}^{ola} + z_{ijk}^{ola}, \tag{12}$$

$$\theta_{ijkq}^{ola} = \Theta_{ijkq}^{ola} + (1 - x_{ijk}^{ola}) \cdot \delta_t, \tag{13}$$

$$AF_{ijkq}^{ola} = 1 - \left(1 - AF_{ola}^{sleep}\right) \frac{\theta_{ijkq}^{ola}}{\Delta_t} + \chi^{ola} \frac{c_{ijkq}^{ola}}{2}, \tag{14}$$

$$\forall (i, j) \in E, \forall k \in K_{ij}, \forall q \in O_{ijk}.$$

Specifically, (11) detects if there is a power state transition for OLAs on fiber link (i, j, k), by taking into account the power state during current time period x_{ijk}^{ola} and the power state during the previous time period X_{ijk}^{ola}. The total number of power state transitions from the beginning of the simulation up to the current time period is computed by (12). Moreover, (13) computes the total amount of time spent in SM by each OLA installed on fiber link (i, j, k). Finally, (14) computes the total AF for the OLAs installed on fiber link (i, j, k).

Similarly to the OLAs, the constraints (15)–(18) are used to derive the AF for the LCs.

$$\begin{cases} x_{n\phi}^{lc} - X_{n\phi}^{lc} & \leq z_{n\phi}^{lc} \\ X_{n\phi}^{lc} - x_{n\phi}^{lc} & \leq z_{n\phi}^{lc} \end{cases}, \tag{15}$$

$$c_{n\phi}^{lc} = C_{n\phi}^{lc} + z_{n\phi}^{lc}, \tag{16}$$

$$\theta_{n\phi}^{lc} = \Theta_{n\phi}^{lc} + (1 - x_{n\phi}^{lc}) \cdot \delta_t, \tag{17}$$

$$AF^{lc}_{n\phi} = 1 - \left(1 - AF^{sleep}_{lc}\right) \frac{\theta^{lc}_{n\phi}}{\Delta_t} + \chi^{lc} \frac{c^{lc}_{n\phi}}{2}, \qquad (18)$$
$$\forall n \in N, \phi \in \Phi_n.$$

D. Additional Constraints on the AF

The PF model takes decisions on the power state of the devices at the current traffic period. However, a power state decision at current time slot may have an influence on future time periods. This is specially true for the FMC, which depend on the AF. More in depth, the AF increases with the number of power state transitions and this process is difficult and time consuming to be recovered. Focusing on OLAs, the AF in SM AF^{sleep}_{ola} in (14) tends to have a marginal impact compared to the weight of power state changes in χ^{ola}, since this last term is multiplied by the number of power state transitions c^{ola}_{ijkq}. A similar reasoning applies also to the AF of the LCs in (18). As a result, it is also important to limit the AF increase over time. To solve this issue, we introduce a threshold on the AF. If the current AF of the device is higher than the threshold value, then the device cannot be put into SM. In this way, we limit the impact of AF increase (and consequently the increase of the FMC) in the future. More formally, the constraints (19)–(22) aim at limiting the AF degradation of the considered devices.

$$AF^{ola}_{ijkq} - \rho^{ola} \le \alpha \cdot h^{ola}_{ijkq}, \qquad (19)$$
$$X^{ola}_{ijk} + h^{ola}_{ijkq} \le x^{ola}_{ijk} + 1, \qquad (20)$$
$$\forall (i,j) \in E, \forall k \in K_{ij}, \forall q \in O_{ijk}.$$
$$AF^{lc}_{n\phi} - \rho^{lc} \le \alpha \cdot h^{lc}_{n\phi}, \qquad (21)$$
$$X^{lc}_{n\phi} + h^{lc}_{n\phi} \le x^{lc}_{n\phi} + 1, \quad \forall n \in N, \phi \in \Phi_n. \qquad (22)$$

Specifically, (19) identifies if an OLA has an AF greater than the threshold. If the threshold condition is not satisfied, (20) prevents the associated OLA from being put into SM. Finally, constraints (21) and (22) ensure the threshold condition also for the LCs.

E. Costs and Revenues Computation

Finally, we compute the costs and the revenues by adopting the models detailed in Section III.

$$C_M = \delta_t \left[C^{ola}_r \cdot MTTR^{ola} \cdot \left(\sum_{(i,j)\in E} \sum_{k \in K_{ij}} \sum_{q \in O_{ijk}} AF^{ola}_{ijkq} \cdot \gamma^{on}_{ola} \right) + C^{lc}_r \cdot MTTR^{lc} \cdot \left(\sum_{n=1}^{|N|} \sum_{\phi=1}^{\Phi_n} AF^{lc}_{n\phi} \cdot \gamma^{on}_{lc} \right) \right]. \qquad (23)$$

$$C_E = C_{Wh} \cdot \delta_t \cdot \left[\left(\sum_{i=1}^{|N|} \sum_{j=1}^{|N|} \sum_{k=1}^{|K_{ij}|} x_{ijk} \sum_{q=1}^{|O_{ijk}|} P^{ola} \right) + \left(\sum_{n=1}^{|N|} \sum_{\phi=1}^{\Phi_n} x^{lc}_{n\phi} \cdot P^{lc} \right) \right]. \qquad (24)$$

$$U = U^{lp} \cdot \delta_t \cdot \sum_{s=1}^{|N|} \sum_{d=1}^{|N|} r_{sd}. \qquad (25)$$

More in depth, (23) computes the FMC C_M from OLAs and LCs. In addition, (24) computes the EC C_E. Finally, (25) computes the revenue U from clients by adopting the definition from (4).

F. Overall Formulation

The objective of the PF problem is the maximization of network profitability of the operator for the current time period:

$$\max \left(U - C_M - C_E \right). \qquad (26)$$

subject to constraints (6)–(25).

G. Complexity Analysis

We assess the complexity of the proposed formulation in terms of number of variables and constraints. Let us denote K_{MAX}, O_{MAX}, and ϕ_{MAX} as the maximum number of fibers on a single link, the maximum number of OLAs on a single fiber, and the maximum number of LCs on a single node, respectively. We consider the worst-case scenario by assuming the maximum number of each set, as the number of fibers on a link, the number of OLAs on a single fiber, and the number of LCs on a single node may vary.

We initially focus on the variables. Variables f^{sd}_{ijk} have size equal to $|N|^4 \times K_{MAX}$. Variables r_{sd} have size $|N|^2$. Both x^{ola}_{ijk} and z^{ola}_{ijk} are matrices of size $|N|^2 \times K_{MAX}$. The variables related to OLAs, namely c^{ola}_{ijkq}, θ^{ola}_{ijkq}, AF^{ola}_{ijkq}, and h^{ola}_{ijkq}, have size equal to $|N|^2 \times K_{MAX} \times O_{MAX}$. In addition, the LC related variables, namely $x^{lc}_{n\phi}$, $c^{lc}_{n\phi}$, $\theta^{lc}_{n\phi}$, $z^{lc}_{n\phi}$, $AF^{lc}_{n\phi}$, and $h^{lc}_{n\phi}$ have size equal to $|N| \times \Phi_{MAX}$. Therefore, the overall number of variables is in the order of $|N|^4 \times K_{MAX} + |N|^2 + 2 \times |N|^2 \times K_{MAX} + 4 \times |N|^2 \times K_{MAX} \times O_{MAX} + 6 \times |N| \times \Phi_{MAX}$.

Focusing instead on the number of constraints, (6) requires $|N|^3$ constraints, while (7) requires $|N|^2$. In (10), $|N|$ constraints are required. Moreover, $|N|^2 \times K_{MAX}$ constraints are required by (8), (9), (11). Equations and inequalities (12), (13), (14), (19), (20) amount to $|N|^2 \times K_{MAX} \times O_{MAX}$ constraints. Eventually, (15), (16), (17), (18), (21), (22) exploit $|N| \times \Phi_{MAX}$ constraints. Clearly, (23), (24), (25) are three constraints in total. Overall, the entire formulation requires $|N|^3 + |N|^2 + |N| + 3 \times |N|^2 \times K_{MAX} + 5 \times |N|^2 \times K_{MAX} \times O_{MAX} + 6 \times |N|^2 \times \Phi_{MAX}$ constraints. In this case, it is interesting to note that the formulations targeting only the minimization of the energy require $|N|^3 + 2 \times |N|^2 \times K_{MAX}$ constraints. However, the impact (in terms of additional constraints) of the lifetime-aware formulation is limited, for two main reasons: *(i)* the change in the power state on a fiber affects the power states of all the OLAs installed on it (as reported in (12)), and *(ii)* the HW parameters tend to be similar across the set of OLAs installed on the same fiber, resulting in a similar behavior in terms of AF given the same number of transitions and time spent in SM.

VI. SCENARIO AND PARAMETERS SETTING

We first detail the network scenario under consideration, and then we report the main intuition to set the input parameters of our model.

A. Network Scenario

Optical network topology: Similarly to [16], we use the Géant physical topology. The topology is a result of the network design process described in [33]. The Mixed-Integer Linear Programming (MILP) formulation from [33] determines the total number of installed fibers for each link in the network, considering 80 wavelengths per fiber. The number of Optical Line Amplifiers (OLAs) installed at each fiber link is derived from the length of the link assuming an 80 km span between OLAs.

Traffic data: We consider two traffic periods during a day, i.e., the low-traffic period 12:00 am – 05:45 am and the high-traffic period 06:00 am – 11:45 pm. In this way δ_t is equal 6 h for the low-traffic period and 18 h for the high-traffic period. Two traffic assumptions are considered for both periods. First, minimum traffic demands r_{sd}^{min} are randomly determined, but parameterized with traffic measurements. Second, a scaling factor is applied to r_{sd}^{min} in order to calculate maximum traffic r_{sd}^{max}. We explain the parametrization of r_{sd}^{min} and r_{sd}^{max} next.

Similarly to [16], we use traffic measurements [34, 35] as basis to determine the number of LightPath (LP) requests. The traffic measurements from [34, 35] (expressed in bps for each node pair in the network at each of the considered 15-minute intervals) are transformed into number of LP requests r_{sd}^{LT} (to be established between each node pair $s, d \in N$) using the dynamic Logical Topology (LT) design reported in [17] (description of detailed data selection is available in [16]).

Based on r_{sd}^{LT}, we generate random traffic demands r_{sd}^{min} according to:

$$r_{sd}^{min} = \max(\lceil (r_{sd}^{LT} + \text{uniform}[-\lambda, \lambda] \cdot r_{sd}^{LT}) \rceil, 0), \tag{27}$$

where the number of demands are always in the interval $[0, r_{sd}^{LT} + \lambda \cdot r_{sd}^{LT}]$.

Finally, the maximum number of LPs r_{sd}^{max} is calculated according to:

$$r_{sd}^{max} = \lceil r_{sd}^{min} \cdot \sigma \rceil. \tag{28}$$

The λ and σ values are assumed to be 5 and 1.2, respectively, for all the experiments carried out in this work. This set of values and the uniform random number distribution are chosen in order to add randomness to the real traffic measurements, while avoid blocking of LP requests.

Line Cards (LCs) installation: The set of LCs installed in the network, i.e., Φ, is defined at the beginning of the simulation experiment. It is determined by the maximum number of LPs each node may receive, based on all the traffic matrices and random variables we introduce in (27) and (28). All the experiment scenarios have the same number of LCs for all the strategies benchmarked in this work. We assume that a LC installed in a node can be used by any fiber link connected to such node. For the Géant topology with random traffic we have 974 OLAs and 1451 LCs installed in order to handle the maximum number of possible traffic demands for all the experiments.

B. Setting of the Input Parameters

We then focus on the setting of the HardWare (HW) parameters in the lifetime model defined in (1). We initially focus on OLAs and the related HW parameters AF_{ola}^{sleep} (i.e., Acceleration Factor (AF) in Sleep Mode (SM)) and χ^{ola} (i.e., the weight for the power switching frequency), which appear in (18) of the Profitability Formulation (PF) formulation. We recall that both these terms have an influence on the lifetime computation and therefore on the associated Failure Management Costs (FMC) of OLAs.

Specifically, AF_{ola}^{sleep} is defined as $AF_{ola}^{sleep} = \gamma_{ola}^{sleep} / \gamma_{ola}^{on}$, where γ_{ola}^{sleep} [1/h] is the lifetime in SM and γ_{ola}^{on} [1/h] is the lifetime when the OLA is always powered on. By expressing the lifetime with the Arrhenius law [13], we can denote AF_{ola}^{sleep} as:

$$AF_{ola}^{sleep} = \frac{e^{-\frac{E_{ola}^{a}}{\mathcal{K} \cdot \mathcal{T}^{sleep}}}}{e^{-\frac{E_{ola}^{a}}{\mathcal{K} \cdot \mathcal{T}^{on}}}}, \tag{29}$$

where E_{ola}^{a} [J/mol] is the minimum activation energy, $\mathcal{K}$ [J/(mol $\cdot$ K)] is the Boltzmann constant, $\mathcal{T}^{sleep}$ [K] and $\mathcal{T}^{on}$ [K] are the temperatures in SM and Active Mode (AM), respectively. In our case, we have considered the following settings: *(i)* $\mathcal{T}^{on} = 329.5$ [K], corresponding to 56.35° Celsius, *(ii)* $\mathcal{T}^{sleep} = 305$ [K], corresponding to 31.85° Celsius, $\mathcal{K} = 8.314472$ [J/(mol $\cdot$ K)], $E_{ola}^{a} = 54000$ [J/mol], which is a value slightly higher than the ones reported for chip components [36] (i.e., we take a conservative assumption). With these settings, we get $\gamma_{ola}^{on} = 10^{-5}$ [1/hour] (which is in line with the measurements reported in [13, 37, 38]) and $AF_{ola}^{sleep} = 0.2$. The reason for these settings are the following: *(i)* we adopt the assumption that the temperature of the device in SM is slightly higher than the external environment temperature; *(ii)* $\mathcal{T}^{on}$ and $\mathcal{T}^{sleep}$ fall inside the operation limits of HW infrastructure (see, e.g., the measurements in [39] for server machines), *(iii)* we consider the activation energy of the chip components, i.e., solder joints, which are deployed in nowadays hardware and are subject to fatigue effects (see, e.g., the survey [15]).

The second HW parameter is the weight for power state frequency χ^{ola} which is defined as $\chi^{ola} = \frac{1}{\gamma_{ola}^{on} N_F^{ola}}$ [h/cycle], where γ_{ola}^{on} [1/h] is again the lifetime in AM (taken from the previous computation), while N_F^{ola} is the number of cycles to failure. In our case, we have set $N_F^{ola} = 200000$. This value is slightly higher than the one obtained from real measurements of the number of cycles to failure of chip components, like for example the ones reported in [40]. Therefore, we believe that the presented analysis is rather conservative (i.e., the impact of power state transitions may be even higher). As a result, we get $\chi^{ola} = 0.5$ [h/cycle].

Focusing on the LCs, we adopt a similar procedure to set the HW parameters AF_{lc}^{sleep} and χ^{lc}. Specifically, AF_{lc}^{sleep} is computed from the Arrhenius law with the following parameters: *(i)* $\mathcal{T}^{on} = 329.5$ [K], *(ii)* $\mathcal{T}^{sleep} = 305$ [K], $\mathcal{K} = 8.314472$ [J/(mol $\cdot$ K)], $E_{lc}^{a} = 57350$ [J/mol], which is a value slightly higher than E_{ola}^{a} since we assume that the activation energy needed to trigger a failure in a LC is higher than in an OLA (i.e., the LC is designed to better sustain power state variations). As a result, $\gamma_{lc}^{on} = 2.9 \cdot 10^{-6}$ [1/hour] (which is in line with the previous work [13, 41]) and $AF_{lc}^{sleep} = 0.2$. Finally, we set $\chi^{lc} = 0.5$ [h/cycle] by assuming $N_F^{lc} = 650000$

TABLE IV
SUMMARY OF THE INPUT PARAMETERS.

Parameter	Value	[Source] / Appear in Eq.
C_{Wh}	$1.6 \cdot 10^{-4}$ [USD/Wh]	[13, 30, 42] / (3), (24)
U^{lp}	2 [USD/hour]	(4), (25)
λ	5 [units]	(27)
σ	1.2 [units]	(28)
C_r^{ola}	380 [USD/hour]	[13, 30, 38, 43] / (23)
γ_{ola}^{on}	10^{-5} [failure/hour]	[13, 37, 38] / (23)
$MTTR^{ola}$	6 [hour]	[13, 30, 38] / (23)
P^{ola}	110 [Watt]	[44] / (24)
C_r^{lc}	190 [USD/hour]	[13, 30, 43, 45] / (23)
γ_{lc}^{on}	$2.9 \cdot 10^{-6}$ [failure/hour]	[13, 41] / (23)
$MTTR^{lc}$	2 [hour]	[13, 30] / (23)
P^{lc}	374 [Watt]	[13, 30] / (24)
AF_{ola}^{sleep}	0.2 [units]	[Section VI-B] / (14)
χ^{ola}	0.5 [h/cycle]	[Section VI-B] / (14)
ρ^{ola}	1.0 [units]	(19)
AF_{lc}^{sleep}	0.2 [units]	[Section VI-B] / (18)
χ^{lc}	0.5 [h/cycle]	[Section VI-B] / (18)
ρ^{lc}	60.0 [units]	(21)

(we assume here again that a LC is less susceptible to power state change events than the OLAs as showed in [13]).

Finally, Table IV summarizes the setting of the HW parameters, as well as the setting for the other parameters used by the PF model. For each parameter, the table reports the reference(s) for the adopted value(s), as well as the equation in the PF model where the parameter is used.

VII. PERFORMANCE ASSESSMENT

We first introduce the strategies selected for assessing the performance of the Profitability Formulation (PF) together with their respective evaluation metrics. Then we present a number of simulation results, followed by a sensitivity analysis.

A. Benchmark Strategies

We benchmark PF against 3 literature strategies, namely Energy-Aware (EA) [46], Shortest Path (SP) [47] and Lifetime-Aware Formulation (LAF) [16]. More specifically, the EA strategy [46] is a purely energy-aware Integer Linear Programming (ILP) formulation targeting solely the minimization of the Electricity Costs (EC). The SP strategy [47] is an ILP formulation that always minimizes the lengths of established LightPaths (LPs) while keeping all the installed devices in Active Mode (AM). Finally, the LAF strategy [16] is a Mixed-Integer Linear Programming (MILP) formulation that targets the minimization of the Acceleration Factor (AF), and consequently only the Failure Management Costs (FMC). Table V summarizes the considered strategies and the costs/revenue taken into account by each of them. Additionally, the referenced EA, SP and LAF strategies do not consider elastic traffic. In order to perform a fair comparison of the strategies, the LP requests r_{sd} chosen by the PF model is used as input for the benchmark strategies.

TABLE V
CONSIDERED STRATEGIES AND METRICS.

Strategy	Failure Management Costs	Energy Costs	Revenues from Clients
EA [46]	No	Yes	No
SP [47]	No	No	No
LAF [16]	Yes	No	No
PF	Yes	Yes	Yes

B. Evaluation Metrics

We consider the following metrics to evaluate the different strategies: *(i)* FMC introduced in Section III-A; *(ii)* EC introduced in Section III-B; *(iii)* operator revenue from clients introduced in Section III-C; *(iv)* network profitability introduced in Section III-D; and *(v)* Energy-Maintenance (EM) break-even point. All Optical Line Amplifier (OLA) and Line Card (LC) devices installed in the network are included in these metrics.

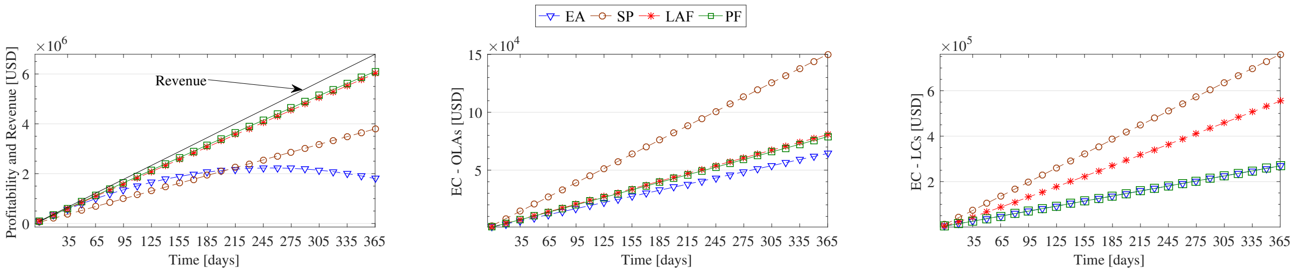
The EM break-even point $U_{breakeven}^{lp}$ [USD/h], in the context of this work, is defined as the ratio between the accumulated costs and the number of LP hour established. Formally, $U_{breakeven}^{lp}$ for a given time slot $\delta_t[h]$ is defined as:

$$U_{breakeven}^{lp} = \frac{C_M + C_E}{\left(\sum_{s=1}^{|N|} \sum_{d=1}^{|N|} r_{sd}\right) \cdot \delta_t}. \tag{30}$$

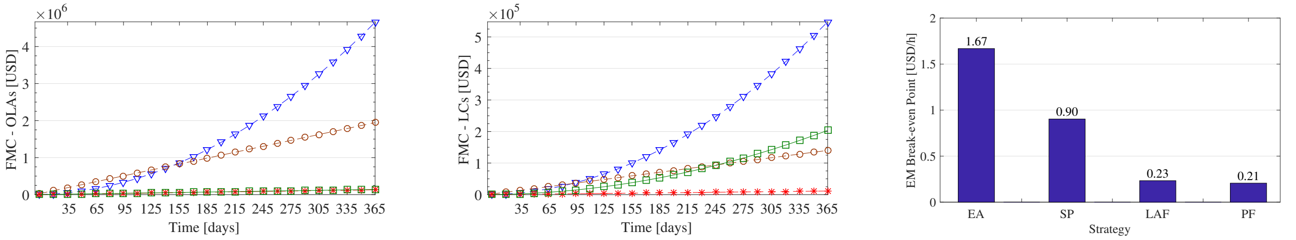
Intuitively, the lower the EM break-even point $U_{breakeven}^{lp}$ is, the higher the profit the operator can potentially obtain. Therefore, such metric can be used to denote the ability of a given strategy to reduce the energy and failure management costs while maximizing the revenue. After calculating the EM break-even point for each traffic period, it is possible to calculate the average EM break-even point for a given time span. The average EM break-even point value at the end of a time span is computed as the average EM break-even point over time.

C. Results

In order to evaluate the different strategies, a custom-built Java-based simulator specifically tailored to the multi-period management of optical core network is used. All the optimization problem instances are solved to optimality by interfacing our simulator with the Gurobi Solver [48] v6.5 on a Linux workstation with 8 CPUs clocked at 2.67 GHz and with 16 GB of RAM. Considering then the simulation setup, the power state of OLAs and LCs is initially set to Sleep Mode (SM). Then, for each strategy, we solve the associated ILP or MILP for the current time slot, thus obtaining the LP routing and the power states for each OLA and LC, which are used to calculate different evaluation metrics. Each instance of EA or SP problem requires 1–3 minutes to be solved, whereas each instance of LAF or PF problem requires 1–60 seconds to be solved. The simulation is repeated over a total time period of one year, with 2 traffic periods per day. The results are averaged over 30 seeds, used for generating the traffic demands. The confidence interval with respect to the profitability value is 5% or lower with 95% of confidence level.



(a) Cumulative profitability and revenue.
(b) Cumulative EC for OLAs.
(c) Cumulative EC for LCs.



(d) Cumulative FMC for OLAs.
(e) Cumulative FMC for LCs.
(f) Average EM break-even point.

Fig. 3. Cumulative network profitability and each one of its components: revenue, Failure Management Costs (FMC) and Electricity Costs (EC) for OLAs, FMC and EC for LCs, and Energy-Maintenance (EM) break-even point at the end of 1 year.

TABLE VI
PERFORMANCE METRICS AT THE END OF THE CONSIDERED TIME PERIOD.

Algorithm	**Profitability [USD]**	**Energy Costs [USD]**		**Failure Management Costs [USD]**		**Operator Revenue [USD]**
		OLAs	LCs	OLAs	LCs	
EA [46]	1.8 M (-70.4%)	64 k (-57.1%)	268 k (-64.6%)	4.6 M (+35.1%)	547 k (+47.6%)	6.8 M
SP [47]	3.8 M (-37.7%)	150 k (0%)	760 k (0%)	1.9 M (+14.1%)	140 k (+11.4%)	6.8 M
LAF [16]	6.0 M (-0.02%)	80 k (-46.2%)	554 k (-27.1%)	128 k (0%)	11 k (0%)	6.8 M
PF	6.1 M (0%)	78 k (-47.5%)	269 k (-64.5%)	139 k (+0.08%)	203 k (+17.0%)	6.8 M

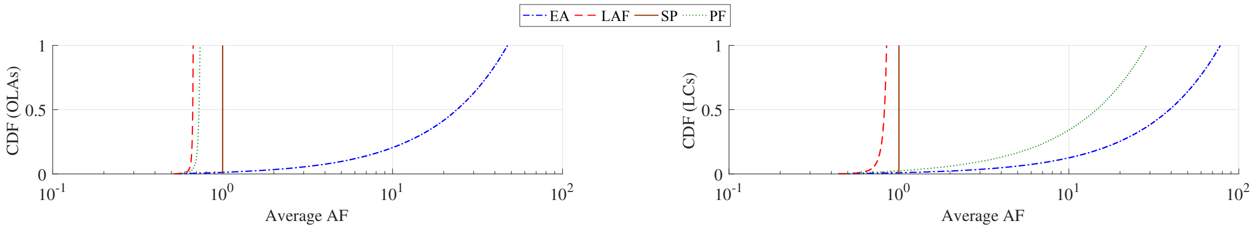
Fig. 3 presents the performance results over the one year experiment. Each data point represents 15 days, starting from the 5th day. In addition, Table VI reports the numerical values obtained at the end of the simulation. Focusing on these results, Fig. 3a presents the cumulative network profitability and operator revenue for all the strategies. The revenue line in the figure represents the cumulative revenue value for any of the strategies, i.e., all the strategies provision the same number of LPs, thus they have the same revenue. The proposed PF strategy achieves the highest profitability (i.e., around 6 million USD at the end of the year), while the profitability of SP and EA are much lower (i.e., less than 4 million USD). In addition, the profitability of the PF surpasses the profitability of the LAF strategy by the significant 84.5 thousand USD.

For the offered traffic matrices, the PF solution always chooses to establish the maximum number of LPs $r_{sd} = r_{sd}^{max}$ for each node pair $s, d \in N$. Such behavior can be explained by the fact that the traffic variation between minimum and maximum number of LPs occurs only for source-destination node pairs which have traffic, according to (28). In this case, the extra costs incurred by establishing the maximum number of LPs come mainly from the activation of LCs. Furthermore, the network has enough capacity to accommodate the maximum number of lighpaths, i.e., blocking does not influence the number of established LPs r_{sd}.

Eventually, we can notice that the EA is very close to PF until around the second month. After this point, the profitability of EA starts sharply decreasing, dropping significantly at the end of the experiment. On the contrary, we can notice that SP achieves positive profitability, but much lower than PF at the end of the year.

To give more insights, Figs. 3b and 3c show the EC for OLAs and LCs, respectively. Intuitively, SP and EA strategies present opposite behavior, with SP incurring the highest and EA achieving the lowest EC. LAF presents intermediate EC values between EA and SP. It means that some devices are kept in AM to avoid lifetime degradation, increasing EC. In addition, the PF strategy presents an intermediate EC (particularly for LCs), since balancing between revenue and costs is explicitly targeted in this case. Finally, we can notice that the total EC of LCs is higher than the one of OLAs.

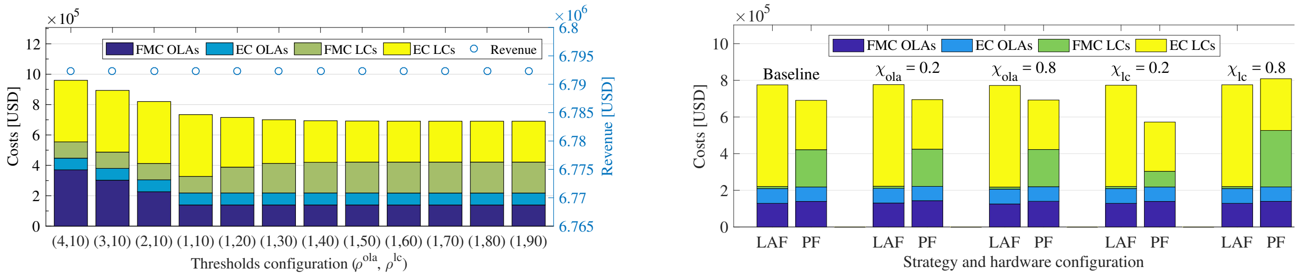
Figs. 3d and 3e report the FMC. In this case, the EA strategy tends to notably increase the costs, as a higher number of power state transitions are introduced over time, leading to an increase of the AF. The FMC of this strategy are higher than the EC in the long term (i.e., at the end of the 1-year experiment). This explains the sharply decreasing trend in profitability of EA observed in Fig. 3a. As expected, the LAF strategy obtains the lowest FMC, as this term is explicitly minimized in the objective function. In the SP case, the FMC are higher than LAF, since this strategy does not exploit the SM to increase device lifetime. Finally, we can see that the PF strategy achieves low FMC for OLAs while slightly increases this cost for LCs. This is due to the fact that the proposed formulation always selects the wisest solution to balance between the costs and the revenue.



(a) AF CDF for OLAs.

(b) AF CDF for LCs.

Fig. 4. Cumulative Distribution Function (CDF) of the average Acceleration Factor (AF) at the end of the 1-year experiment.



(a) Costs and revenue for different configurations of ρ^{ola} and ρ^{lc} using PF.

(b) Costs for different HW parameters using LAF and PF.

Fig. 5. Failure Management Costs (FMC) and Electricity Costs (EC) costs for OLAs and LCs at the end of one year considering (a) different configurations of thresholds ρ^{ola} and ρ^{lc} when using the Profitability Formulation (PF) model and (b) different HardWare (HW) parameters using Lifetime-Aware Formulation (LAF) and PF w.r.t. the baseline where AF_{ola}^{sleep} = 0.2, χ_{ola} = 0.5, AF_{lc}^{sleep} = 0.2 and χ_{lc} = 0.5.

In the following, we move our attention to the analysis of the EM break-even point metric. Ideally, this metric should be kept as low as possible to allow higher network profits. Fig. 3f reports the obtained results for all the strategies at the end of the 1-year experiment. The lowest EM break-even points are achieved by the LAF and the PF strategies, while all the others perform consistently worse. In general, it shows that strategies considering FMC are more effective in lowering the EM break-even point. Although the EM break-even point of LAF and PF looks close to each other, we recall that the PF strategy allows an additional profit of more than 84.5 kUSD w.r.t the LAF one at the end of the year.

Fig. 4 presents the CDF of the average AF for OLAs and LCs. The figure helps us to better understand how the FMC are influenced by the AF values of the devices. The SP strategy achieves an AF equal to one by definition, as all the devices are kept in AM during the entire experiment. The highest AF is reached by the EA, which is agnostic about the lifetime. For EA, the average AF is around 47 and 77 for the OLAs and the LCs, respectively. It means that the lifetime of the devices is reduced by a factor of 47 for OLAs and 77 for LCs when the EA strategy is adopted. On the contrary to EA, the lowest AF is achieved by the LAF strategy. Finally, the PF strategy obtains low average AF values for the OLAs and intermediate values for the LCs. The reason of such behavior lies in the fact that LCs consume more electricity than OLAs, thus it makes sense to change their power states more frequently to save electricity rather than purely focusing only on FMC.

D. Sensitivity Analysis

Real-world deployments comprise devices with different characteristics. When looking at the proposed strategy, different devices deployed in the network might be impacted differently by the power state transitions. For this reason, in this section we focus on a sensitivity analysis of the impact that different thresholds and HW parameters values might have on the costs, as shown in Fig. 5.

Focusing on the threshold configuration presented in Fig. 5a, we recall that these thresholds are able to limit the future increase of the AF, and consequently of the FMC, as reported in Section V-D. Intuitively, when the thresholds are set to the lowest values, the PF strategy is more conservative in terms of lifetime, resulting in a general reduction of FMC, but introducing an increase of the EC. When the thresholds are increased, the FMC tend to follow the same trend, while the EC tend to be decreased. This trend is particularly clear from the observation of the LCs costs. The best setting to achieve the lowest costs is to set $\rho^{ola} = 1$ and $\rho^{lc} \geq 60$, therefore these are the values used in the simulations (see Table IV). The high value of ρ^{ola} in comparison to ρ^{lc} means that it is important to limit the AF increase for the OLAs. On the contrary, higher AF degradation can be accepted for the LCs, as the possible electricity savings are higher than in the case of OLAs. Fig. 5a also reports the revenue in the secondary y-axis. The same revenue is obtained for all threshold settings meaning that all requested lightpaths r_{sd}^{max} are always established.

In the last part of our results, we assess the performance of LAF and PF for different HW parameter values, as reported in Fig. 5b. Besides the HW parameters AF^{sleep} and χ for OLAs and LCs, all the remaining simulation parameters are set according to Table IV. When HW parameters are varied for OLAs, there are no major cost variations (see the three bar pairs starting from the left of the figure).

The opposite happens when the LCs HW parameters are varied (namely in the first, fourth, and fifth bar pairs in Fig. 5b). In this case, there is a significant difference between the performance of PF and LAF. For example, when χ_{lc}=0.2 (the fourth bar pair), PF leads to 25% cost savings compared to LAF. This happens because the variations of the power states have a smaller impact on the maintenance costs, i.e., when devices are designed to be robust to power changes. As a result, LAF becomes too conservative, since it limits the energy saving. On the contrary, PF is able to account for these aspects.

The only case where PF seems to perform worse than LAF is with χ_{lc}=0.8 (the fifth bar pair in Fig. 5b). This value refers to devices that are more susceptible to failures as a consequence of power state changes. However, the performance of PF is influenced by the value of ρ^{lc} that has been kept constant in all the cases of the sensitivity analysis in order to make a fair comparison. On the opposite, for PF, ρ^{lc} can be tuned in order to limit the lifetime degradation of each LC. In this case, an adjustment of the PF parameters can mitigate such behavior by allowing a lower lifetime degradation for LCs.

VIII. FINAL REMARKS AND FUTURE WORK

We have targeted the profitability in an optical core network, by jointly managing the Electricity Costs (EC), the Failure Management Costs (FMC) derived from the activation/deactivation of Line Cards (LCs) and Optical Line Amplifiers (OLAs), and the revenues from clients. After formally defining the network profitability and optimally formulating the problem to maximize it, we have presented a detailed set of results from a realistic scenario. Our findings show that the proposed Profitability Formulation (PF) strategy achieves better performance compared to solutions only minimizing the EC, the FMC, or targeting the length of the LightPath (LP) requests. In addition, the following remarks should be taken into account.

While the failure costs originate from a physical phenomena, how significant this effect is across vendors, technologies, deployment granularity, and deployment sizes is an open issue. To partially shed light on these aspects, we provided a sensitivity analysis of the HardWare (HW) parameters, clearly showing the trade-offs that emerge. In particular, when devices are more robust to power state changes (i.e., for low values of χ_{ola} and χ_{lc}), PF is able to perform clearly better than Lifetime-Aware Formulation (LAF). From our observation, it is reasonable to assume that the best settings for the values of ρ^{ola} and ρ^{lc} are dependent on network topology and traffic profile. Different network topologies come with different link lengths, which in turn defines the number of OLAs that each power state transition will impact. At the same time, the traffic profile defines how a given traffic period is different from the next one. As a next step, we plan to investigate a methodology to compute the best values of ρ^{ola} and ρ^{lc}.

The traffic requests profiles used in the paper have a degree of flexibility, where a client specifies a minimum and maximum amount of traffic that will need to be supported. Our assumption is that an operator needs always to guarantee support for the minimum amount, while extra traffic can be provisioned if free resources are available. For instance, the new applications such as adaptive video streaming [49] are in line with serving traffic between a minimum and a maximum bitrate. Hence, the minimum traffic level is always supported, and it is never traded in to reduce the network power consumption. Eventually, energy efficiency is achieved by letting the Integer Linear Programming (ILP) re-route lightpaths to offload lightly utilized fiber links. This way of computing the revenue may be seen as a stretch, but operators can now leverage on the recent advances on network control plane (i.e., slicing) to offer more granular and flexible services to their clients. This apparatus is crucial for network operators to enable fast deployment of new services, and to offer more flexibility for their customers [50]. Following the same reasoning, we believe the current monthly-based billing model will shift toward the cloud computing billing model introduced by cloud service providers [51], in which the users are billed on a pay-per-use monthly basis, in accordance to the amount of resources that they consumed.

As a final remark, this work focused solely on HW reliability. However, SoftWare (SW) reliability is also extremely important as SW grows in complexity and importance for the correct functioning of HW, especially in the networking field (see e.g., [52]). In particular, whenever a device changes its operating mode there is the possibility of a failure due to SW problems. Eventually, the type of SW failures that impact networking devices may be automatically recovered or even repaired by executing remote operations, e.g., by simply rebooting the device [53, 54]. However, HW failures, which are the focus of this work, usually can not be fixed remotely and the failed device has to be physically replaced or repaired. These operations tend to increase both the reparation time and cost when compared to the case of SW failures. We plan to address the topic of SW reliability as future work.

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