Energy Efficiency Versus Reliability Performance in Optical Backbone Networks [Invited]

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***Abstract*—Improving the energy efficiency in telecommunication networks has been one of the main research topics of the past few years. As a result, many energy efficient algorithms have been proposed, some focusing on maximizing only the energy savings, others considering also the impact that green strategies have on other network performance metrics, e.g., delay, utilization of network resources, and blocking probability. The aim of this paper is to provide new insight on the impact of energy efficient strategies, i.e., investigating the trade-off between green network operations and the reliability performance of optical backbone devices. The study is motivated by the intuition that energy efficient strategies are usually based on putting unutilized devices in power saving (sleep) mode, which can have some side effects (e.g., frequent on/sleep switching, and/or high fiber link utilization) that may affect the working conditions of a device. To better understand these phenomena, this paper presents a number of models aimed at estimating the reliability performance changes of a device as a function of its average working temperature, of its temperature variations, and of its average occupancy. These models are then used to carry out a study both at the component and at the network levels. The study at the component level shows that erbium-doped fiber amplifiers (EDFAs) are critical devices, i.e., their achievable energy savings might not cover the additional reparation costs resulting from their reliability performance degradation. Similar findings are reached also with the network level study. In summary, it can be concluded that the use of energy efficient routing algorithms based on setting EDFAs in sleep mode may not always be beneficial.**

***Index Terms*—Energy efficiency; Erbium-doped fiber amplifiers (EDFA); Green routing; On/sleep switching; Optical backbone networks; Reliability.**

I. INTRODUCTION

It is estimated that communication networks are responsible for 1.8% of the total electricity consumption worldwide [1]. This number is expected to grow with an annual rate (around 10%) that is higher than the pace at which the overall demand for electricity increases (around 3%) [1]. Many energy efficient approaches have been proposed to reduce the energy consumption of communication networks [2]. Most of them are based on the idea of putting idle network devices in sleep mode, a state in which components consume less energy compared to their "fully operational" mode.

Energy efficient techniques, on the other hand, may have a negative impact on some network performance metrics. For example a number of energy efficient schemes have been evaluated with respect to their impact on delay [3,4] or blocking probability [5,6]. Sleep-mode-based green approaches may also negatively affect the reliability performance of network devices [7–9]. This is mainly due to the cyclic temperature changes caused by the switching between fully operational and sleep modes (i.e., *thermal cycling*). Such variations can accelerate the deterioration of a device [7,10,11], in particular its solder joints [12].

The reliability performance of a device might also be sensitive to other traffic related aspects as a result of the application of energy efficient strategies. For example, green routing strategies in backbone networks tend to concentrate the traffic on a subset of the network elements [6], with the result that fiber link occupancy is on average increased. This is done to maximize the number of devices that can be put in sleep mode. On the other hand, there are components like pump lasers in erbium-doped fiber amplifiers (EDFAs) that may have a shorter than normal lifetime if forced to work at high optical output power levels (i.e., as a result of a higher fiber link occupancy).

The above considerations are extremely important because any change in the reliability performance of a network device impacts the network operational expenditure (OPEX) in terms of extra failure reparation costs [9]. This aspect cannot be neglected when considering the overall benefits of a green strategy. In other words, it is important to make sure that the potential savings brought by a reduced electricity bill are not overcome by the extra reparation costs resulting from a reduced reliability performance of some network devices. The work in [13] was one of the first to point out this aspect and to assess for a number of active components the maximum allowable reliability performance degradation as the result of the use of an energy efficient mechanism.

The work in this paper is built upon the initial study done in [13] and presents a refined framework able to assess the reliability performance degradation caused by energy efficient routing and wavelength assignment (RWA)

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schemes applied in optical backbone networks. To identify the devices that are most susceptible to reliability performance degradations when targeted by energy efficient algorithms, two indicators are introduced: $d_{\max}$ and $t_{\min}^{\text{off}}$. The first one (i.e., $d_{\max}$) is defined as the maximum tolerable (mean) lifetime degradation, where the overall OPEX does not increase after an energy efficiency mechanism is used. The second indicator (i.e., $t_{\min}^{\text{off}}$) is defined as the minimum amount of time a device should be kept switched off to save enough energy to compensate for the reparation cost of a single failure. In the remainder of this paper, the term *lifetime* corresponds to the *mean lifetime* of a device.

In addition to these two indicators this paper introduces a new concept called the *reliability profile* of a device. This concept is used to understand how the reliability performance of a component varies as a function of the amount of traffic that the device carries. This is an important aspect to consider because, as it was already mentioned, some green RWA strategies tend to increase the average value of the fiber link utilization when maximizing the number of EDFAs that can be put in sleep mode.

A trade-off assessment (in terms of OPEX) between energy efficiency benefits and reliability performance degradation is carried out both at the component and at the network levels. The study at the component level shows that the EDFA is the device with the lowest $d_{\max}$, or equivalently the highest $t_{\min}^{\text{off}}$. In addition, the same study highlights how EDFAs have a reliability profile by which their lifetime degrades at higher utilization levels. These findings motivate the need to take a closer look at the overall network OPEX values when green RWA algorithms based on setting EDFAs in sleep mode are used. An assessment study is performed by applying a green RWA strategy called Weighted Power-Aware Lightpath Routing (WPA-LR) [6] to different network topologies. The simulation results confirm the initial intuition that energy efficient techniques setting EDFAs in sleep mode may have a negative impact on the overall OPEX.

The remainder of the paper is organized as follows. Section II presents the models that are used to analyze the reliability performance of a device when subjected to a number of on/sleep switching cycles. Section III presents an analysis of the trade-off between energy savings and reliability performance degradation on a per-component basis. Section IV shows a similar assessment, but this time done at the network level, while Section V provides some concluding remarks.

II. RELIABILITY MODELS

This section presents the key physical phenomena that should be considered when modeling the reliability performance of a device that is periodically set in sleep mode to save energy. Then the concept of the reliability profile is introduced and used to model the reliability performance of a component as a function of its occupancy.

A. Physical Phenomena Impacting Component Reliability Performance

There are several factors that may impact the reliability performance of a component periodically set in sleep mode. They include temperature [14], temperature variation [12,15–17], humidity [18], vibration [19], electromigration [7], and time-dependent dielectric breakdown [7]. The work in this paper focuses only on temperature and temperature variation. Humidity and vibration considerations are excluded since devices used in backbone networks are normally placed in protected locations. Other factors, such as electromigration or time-dependent dielectric breakdown, are relevant mostly when looking specifically at very large scale integration (VLSI) microchips/processors and less applicable to the type of optical network devices currently considered in the paper.[1]

Reliability performance as a function of the temperature can be modeled using the Arrhenius law [14], which defines how much the reliability performance of a device can change if operated at a temperature that is different from the reference one. The Arrhenius law is widely used in accelerated reliability tests to estimate the lifetime of devices. Often, the temperature considered in such tests is much higher than the standard operational temperature of a device, e.g., ≈150°C. Some experimental studies about hard disk drives [20] and datacenter nodes [21] confirm that the average temperature at which a device is operated has a non-negligible impact on the reliability performance. To assess the lifetime variations of a device set in sleep mode, this work adopts the Arrhenius acceleration factor formula [7], assuming the fully operational mode as the reference condition. The acceleration factor $\text{AF}_{\text{Ar\_lifetime}}$ can be calculated using the following formula:

$$\text{AF}_{\text{Ar\_lifetime}} = \frac{L_r}{L_s} = 1 - t_{\text{sleep}}\left(1 - e^{\frac{E_a}{k}\left(\frac{1}{T_r} - \frac{1}{T_s}\right)}\right), \tag{1}$$

where L_r and L_s represent the mean lifetime of the device (expressed in time units, e.g., hours) in the reference (i.e., working) and sleep conditions, respectively; t_{sleep} is the percentage of time spent by the device in sleep mode; E_a is the activation energy [J]; k is the Boltzmann constant [J/K]; while T_r and T_s represent the average temperature [K] in the reference and sleep conditions, respectively. When a device is set in sleep mode, then $0 < t_{\text{sleep}}$, $T_s < T_r$, and as a result $\text{AF}_{\text{Ar\_lifetime}} < 1$. This means that while sleeping a device will experience beneficial effects in terms of increasing lifetime.

The second important factor impacting the reliability performance of a device is temperature variation. Different materials within the same component have different expansion coefficients and consequently suffer from strain and fatigue when the temperature varies, especially if it happens in a cyclic way, i.e., in a situation often referred

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[1] This might not be the case if extensive digital signal processing (DSP) is used together with advanced modulation format, a case currently outside the scope of this paper but that can be considered in a future work.

to as *thermal cycling*. The Coffin–Manson model [15,16] describes the effect of material fatigue of a component induced by thermal cycling, and it is used to estimate the number of temperature cycles that a device can support during its lifetime. The Coffin–Manson model was designed initially for engines and turbines, and it was then extended by Engelmeier [12] and Norris–Lanzberg [17] to model the thermal cycling effects in electronic devices (in particular for solder connections).

In a device, thermal cycling can also be referred to as *power cycling* when it is the result of cyclic transitions between on and sleep states. The work in [11] shows that power cycling has an impact on the reliability performance of a device similar to the one caused by thermal cycling; i.e., it decreases the device lifetime. In addition, power cycling can cause higher and more localized temperature variations, which may occur with a higher frequency compared to thermal cycling. The reliability impact of power cycling is difficult to quantify as it varies with the particular design of a device. On the other hand, when modeling the impact of power cycling on the reliability performance of a device, the important factor to consider is again the temperature variation. This can be done by using the Norris–Lanzberg acceleration factor formula [22]:

$$\mathrm{AF}_{\mathrm{NL\_cycles}} = \frac{N_r}{N_t} = \left(\frac{f_t}{f_r}\right)^a * \left(\frac{\Delta T_t}{\Delta T_r}\right)^b * e^{-\frac{E_a}{k}\left(\frac{1}{T_{\max,r}} - \frac{1}{T_{\max,t}}\right)}, \quad (2)$$

where N_r and N_t represent the average number of temperature cycles during the lifetime of a device in the reference and the test conditions, respectively. Reference conditions correspond to the standard operating mode where on/off switching can be performed for maintenance purposes, while test conditions refer to the case where both maintenance and energy-efficiency-based switching are considered. The values of f_r and f_t represent the thermal cycling frequency in the reference and the test conditions, respectively. The value of f_r is relatively small but not null as equipment is regularly switched off for maintenance purposes. Sleep cycles, on the other hand, add to the regular maintenance cycles, i.e., $f_r < f_t$. The values of ΔT_r and ΔT_t define the difference between the maximum and minimum temperatures [K] during a cycle in both reference and test conditions, respectively, while $T_{\max,r}$ and $T_{\max,t}$ are the maximum operating temperature [K] in reference and test conditions, respectively.

The maximum operational temperature of a device in reference and test conditions is the same (i.e., $T_{\max,r} = T_{\max,t}$). Also if the sleep cycles are long enough to cool down the device completely (i.e., less frequent than 1 cycle/h, as in our case), it can be assumed that $\Delta T_r = \Delta T_t$. As a result, $\mathrm{AF}_{\mathrm{NL\_cycles}}$ becomes a function of the frequency of the test cycles (f_t) only. Assuming that soldering is done using SnAgCu (SAC) eutectic solder (i.e., $a = 0.33$, $b = 1.9$, and $E_a/k = 1414$ [22]), then Eq. (2) can be expressed in terms of an acceleration factor affecting the lifetime and simplified as

$$\mathrm{AF}_{\mathrm{NL\_lifetime}} = \frac{L_r}{L_t} = \frac{N_r * f_t}{N_t * f_r} = \left(\frac{f_t}{f_r}\right)^{1.33}, \quad (3)$$

where L_r and L_t are the mean lifetime of the device (expressed in time units), in the reference and test cases, respectively.

To understand the impact of thermal cycling, the following example can be considered. The majority of recently manufactured network devices are designed to run without any interruptions, except for switching off for maintenance purposes. Let us consider an optimistic case in which a device is maintained once per week. If the same device is subject to more frequent on/sleep switching to save energy, e.g., on average 3.5 times per day [8], its lifetime will be 70 times shorter [Eq. (3)]. According to the Arrhenius law [Eq. (1)], to compensate for this lifetime reduction one would theoretically need to reduce the operational temperature of the device by approximately 140°C. This example shows that thermal cycling may lead to a significant lifetime decrease, which cannot be easily compensated for just by the lower operational temperature conditions of the sleep mode status. A study performed on the nodes in Los Alamos datacenter [21] shows clearly that temperature variation has significantly higher impact on node failure probability than the average operational temperature.

B. Device Reliability Profile

The reliability performance of a device may also depend on its utilization level, i.e., its occupancy. For example, the failure rate of a high-power laser used in an EDFA increases nonlinearly with increasing values of the input current, the output optical power, and the temperature [23]. These parameters can be closely linked to the number of wavelength channels being amplified by an EDFA. Therefore, it might be useful to introduce a new concept, i.e., the *reliability profile*, to describe how the reliability performance of a device varies as a function of its utilization. The utilization is expressed as a percentage of the total capacity of the component. The reliability performance is presented in terms of failure rate, and is normalized to the reliability level of the fully occupied component.

To derive the reliability profile of a device, the reliability performance of each of its main components needs to be assessed separately. The remainder of this section gives an example of how to derive the reliability profile of an EDFA, whose main components are summarized in Table I.

An EDFA is typically composed of three main active components: management electronics, a pump laser, and a thermoelectric cooler (TEC) [24]. The pump laser and the TEC are often found together in one single package. The most recent EDFAs use two pump lasers and two TECs, one on each end of the erbium-doped fiber [24,25]. Assuming that the failure rate of an EDFA is usually around 2000 FITs (failure in time unit corresponding to one failure during 10^9 h) [26], it is possible to derive the per-component failure rate breakdown by analyzing each one of them separately.

TABLE I
EDFA RELIABILITY PROFILE (PER-COMPONENT FAILURE RATE BREAKDOWN AS A FUNCTION OF THE EDFA OCCUPANCY)

	Occupancy = 0%	Occupancy = (0%, 100%)	Occupancy = 100%
EDFA pump laser	5%	Polynomial function (degree 3.5)	50%
TEC	3%	Linear function	36%
Management electronics	14%	Constant function	14%
Total	**22%**	Polynomial function	**100%**

The EDFA pump laser is a high optical power laser. Its failure rate varies in a nonlinear way as a function of the laser output optical power, the current passing through it, and the operating temperature [27], which can be neglected when the pump laser temperature is stabilized by the TEC. For a laser with an output optical power of about 750 mW the failure rate is 500 FITs [23]. Considering that there are two pumps in an EDFA, the failure rate of the two pump lasers will be twice as high, i.e., 1000 FITs, which corresponds to 50% of the total failure rate of an EDFA when fully occupied [28]. The failure rate of the EDFA pump laser is proportional to the electrical current in the power of 3.5 [27]. Assuming that the voltage drop on the pump laser is fairly constant, and that the optical power varies linearly with the number of wavelength channels amplified by the EDFA [26], it can then be derived that the failure rate of the EDFA pump laser has a polynomial dependence with the EDFA's occupancy, measured in terms of the number of amplified wavelength channels.

The TEC is a fairly reliable component. Reference [29] shows that its failure rate is 360 FITs. Taking into account that one TEC is needed for each pump laser, the failure rate of both TECs will be 720 FITs, which corresponds to 36% of the total failure rate of a fully occupied EDFA. It can be assumed that the reliability performance of the TEC decreases with the increasing number of channels to be amplified by the EDFA. This conclusion is based on the observation that the higher is the number of the wavelength channels to amplify, the higher is the optical power level of the pump laser. In turn, this requires the TEC to dissipate a larger amount of heat, resulting in the TEC operating at higher temperatures and consequently possibly experiencing worse reliability performance (i.e., because of the Arrhenius law). Based on the same reasoning, it can also be assumed that the failure rate of the TEC varies linearly as a function of the EDFA's occupancy.

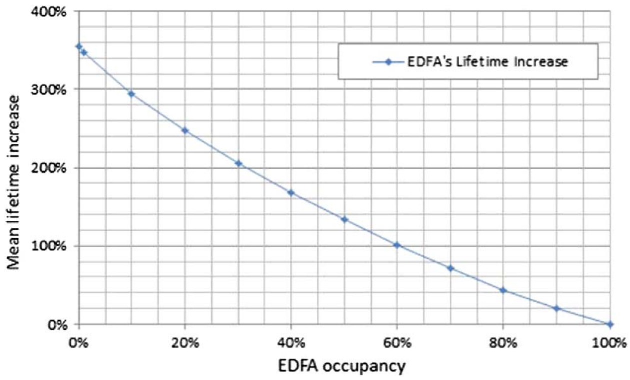

Fig. 1. EDFA lifetime increase as a function of its occupancy.

The management electronics used to control the EDFA is fairly basic. It consists of several analog/digital and digital/analog converters, in addition to a number of electronic operational amplifiers, transistors, and photodiodes. It is available on the market as a specially designed chip, e.g., AM7820 [30] or ADN8820 [31]. The role of the management electronics is to (i) monitor the temperature of the pump laser and the optical power of the input and output signals and (ii) control the voltage and current of the TEC and of the pump laser to make sure that temperature and amplification gains are maintained at the desired levels. The control chip power consumption is very low, e.g., the ADN8820 chipset consumes less than 150 mW, while the AM7820 chipset consumes less than 100 mW. The control operations listed above are done independently of the number of active channels traversing the EDFA, so the control chip will not experience any significant temperature increase, or frequent temperature cycles with varying traffic conditions. Therefore, the reliability performance of the management electronics can be considered independent of the EDFA's occupancy. Knowing the TEC and pump laser contributions to the total value of the EDFA failure rate, it can be assumed that the management electronics accounts for the remaining 14% of the total failure rate when the EDFA is fully occupied and that this value does not change as a function of the EDFA occupancy (see Table I).

Figure 1 presents the EDFA lifetime variations (in percentage) as a function of its occupancy according to the reliability profile presented in Table I. The values of the lifetime variations are normalized to the lifetime values corresponding to the fully occupied EDFA. According to the figure, increasing the number of wavelength channels to be amplified by the EDFA may reduce the lifetime of the device.

Given the reliability models presented so far, it becomes essential to understand to what extent the reliability performance of each core network component can be impacted by temperature variations, temperature cycling, and utilization level. This analysis is shown in the next section.

III. ENERGY EFFICIENCY VERSUS RELIABILITY PERFORMANCE—EQUIPMENT-BASED ANALYSIS

This section presents a per-component analysis to identify which core network devices are the most critical from their reliability performance degradation point of view. A device is defined as *critical* if the cost saving from putting it in sleep mode cannot cover the extra reparation costs deriving from its (possible) lifetime decrease.

To identify the critical devices we use the indicator $d_{\mathrm{max,thr\%}}$, defined as the maximum allowable lifetime decrease that can be accepted without incurring an overall network OPEX increase. Lifetime decrease is expressed in percentage compared to the lifetime of a device in standard operational conditions (i.e., without sleep mode in use). The $d_{\mathrm{max,thr\%}}$ is a function of a potential energy saving threshold defined by thr%. It can be calculated by using the following formula:

$$d_{\mathrm{max,thr\%}} = \frac{\mathrm{thr\%} * P_{\mathrm{eq}} * C_{\mathrm{kWh}}}{\mathrm{thr\%} * P_{\mathrm{eq}} * C_{\mathrm{kWh}} + \frac{\mathrm{FR}}{10^6} * (\mathrm{MTTR} * \mathrm{Pers.} * C_m)} [\%], \tag{4}$$

where C_{kWh} [USD/kWh] is the electricity cost, FR represents the equipment failure rate expressed in FIT, C_m [USD/h] is the hourly rate of a reparation crew member, MTTR [h] represents the mean time to repair, Pers. is the number of reparation crew members, and P_{eq} [W] represents the power consumption of the device in fully operational mode. Equation (4) is based on the models presented in [9].

Another way to assess the criticality of a device is to measure for how long it should be kept switched off to save enough energy to compensate for the reparation cost of a single failure (i.e., $t_{\mathrm{min}}^{\mathrm{off}}$). The higher the value of $t_{\mathrm{min}}^{\mathrm{off}}$, the more critical is the device. The $t_{\mathrm{min}}^{\mathrm{off}}$ value can be calculated by dividing the reparation cost of one failure by the total energy cost of operating the device under examination continuously for one year:

$$t_{\mathrm{min}}^{\mathrm{off}} = \frac{\mathrm{MTTR} * \mathrm{Pers.} * C_m}{8.76 * P_{\mathrm{eq}} * C_{\mathrm{kWh}}} [\mathrm{years}]. \tag{5}$$

Table II presents the values of $d_{\mathrm{max,thr\%}}$ (for three different threshold values) and of $t_{\mathrm{min}}^{\mathrm{off}}$ for a number of active optical components in a backbone network. Other passive components (e.g., splitters, (de)multiplexers, patch panels) are not considered in this study since they are not normally the target of any energy saving mechanism. The values used for the C_{kWh} and C_m are 0.16 USD/kWh [35] and 190 USD/h [9].

As shown in the table, transponders and regenerators are able to sustain a significant degradation of their lifetime without a significant impact on their OPEX values. Their $t_{\mathrm{min}}^{\mathrm{off}}$ values are also very low, and the cost of one additional failure can be covered by setting them off for a reasonable time within their lifetime span. Reconfigurable optical add–drop multiplexers (ROADMs) and optical cross-connects (OXCs) are more sensitive to reliability performance degradation, but their d_{max} and $t_{\mathrm{min}}^{\mathrm{off}}$ values are still acceptable. It can be concluded that, for these components, the impact of on/sleep cycles on their reliability performance is not a major concern. Their extra reparation costs can be compensated for by the energy savings that a green strategy can offer.

However, for EDFAs the value of d_{max} is relatively small, i.e., $d_{\mathrm{max,10\%}} = 2.73\%$, while $t_{\mathrm{min}}^{\mathrm{off}} = 203.3$ years is much higher than the expected EDFA lifetime. This means that there might be instances in which using energy saving strategies based on setting EDFAs in sleep mode may not be beneficial from an overall network OPEX perspective. On the other hand, this intuition has to be verified via a network level study where a number of factors are taken into account, e.g., the network topology, the energy efficient RWA algorithm used, and the average fiber link occupancy. The next section presents a study to verify whether green RWA algorithms based on putting EDFAs in sleep mode are beneficial in terms of overall cost savings.

IV. ENERGY EFFICIENCY VERSUS RELIABILITY PERFORMANCE—NETWORK-BASED ANALYSIS

As shown in the previous section, an EDFA is a critical core network device (from the reliability performance degradation point of view). Therefore, green RWA algorithms based on the idea of putting EDFAs in sleep mode must be further investigated to understand their overall OPEX performance.

The main idea behind a green RWA algorithm [6,36,37] is to prioritize those routes where fiber links are already operational (i.e., with active EDFAs), thus keeping for as long as possible unutilized EDFAs in sleep mode. As a result, the value of the average fiber link occupancy in the network increases [6]. On the other hand, as already shown in Subsection II.B, higher fiber link occupancy values correspond to a worsened EDFA reliability performance (see Fig. 1), thus contributing, together with the effects of thermal cycling (i.e., due to on/sleep switching), to higher failure reparation costs.

TABLE II
CONSIDERED ASSESSMENT INDICATORS FOR DIFFERENT NETWORK D

Equipment	Failure Rate [FIT]	MTTR [h]	Pers.	Power [W]	$d_{\mathrm{max,10\%}}$ [%]	$d_{\mathrm{max,20\%}}$ [%]	$d_{\mathrm{max,30\%}}$ [%]	$t_{\mathrm{min}}^{\mathrm{off}}$ [years]
Transponder [32]	256	2	1	70	*92.0*	*95.8*	*97.2*	*3.9*
Regenerator [32]	256	2	1	70	*92.0*	*95.8*	*97.2*	*3.9*
OXC [33]	5 467	2	1	60	*31.6*	*48.0*	*58.1*	*4.5*
ROADM [34]	3 300	2	1	35	*30.7*	*46.9*	*57.0*	*7.7*
EDFA [32]	2 000	6	2	8	*2.73*	*5.32*	*7.71*	*203.3*

A. Simulation Setup Assumptions

The simulation study is based on a green RWA strategy called Weighted Power Aware Lightpath Routing (WPA-LR) [6] tested on two network topologies, i.e., COST239 [38] and NSFNET [39] under a dynamic lightpath provisioning scenario.

In both network topologies, each fiber link comprises two unidirectional fibers, each one carrying 16 wavelengths. It is assumed that wavelength conversion is not available. Connection requests are bidirectional and their source–destination pairs are uniformly chosen among the network nodes. Connection requests arrive according to the Poisson process, while the service time for each connection request is exponentially distributed with an average holding time equal to one time unit. The traffic load varies from 10 to 420 Erlangs for the COST239 network and from 5 to 210 for the NSFNET network. These values are chosen to investigate low to medium-high load conditions where the network blocking probability does not exceed 10%.

In the simulation study, EDFAs are placed every 80 km and they are the only devices that are set in sleep mode to save energy. The operative status of other network components, such as transceiver, OXCs, or higher layer electronics, never varies (i.e., they are considered to be always on). In this study we consider only the energy savings achieved by putting an EDFA in sleep mode. The power consumed by an EDFA in sleep mode is assumed to be 20% of the power when fully operational. Simulation results are averaged over a series of 10 experiments, each with 10^5 connection requests, ensuring a confidence interval of 5% or better, at the 95% confidence level.

WPA-LR works in the following way. A separate network connectivity graph is considered for each wavelength, i.e., a wavelength plane approach is used. If a specific wavelength on a fiber link is not available (i.e., it is already used to provision a connection request), it does not appear on that specific wavelength plane. This is done to avoid provisioning two different connection requests using the same wavelength on the same fiber link. For an incoming connection request, the path at minimum cost (if any) is computed on each wavelength plane. The path that has the overall minimum cost (among the ones found on each wavelength plane) is then chosen as the route for the connection request. If no paths can be found on any wavelength plane, the connection request is rejected.

The cost function used in WPA-LR works as follows. If a fiber link is not in use, its cost is set to be equal to the power necessary to operate all the EDFAs deployed along its length (i.e., the link energy consumption cost). If, on the other hand, a fiber link is in use its routing cost becomes the product of its power consumption cost and a parameter α that varies in the range (0;1]. Values of α close to 0 encourage WPA-LR to select routes at minimum energy cost, while with $0 < \alpha < 1$ WPA-LR tends to make routing choices that are a compromise between energy consumption minimization and (fiber) resource efficiency maximization. When $\alpha = 1$, the WPA-LR behaves in the same way as the conventional shortest path (SP) approach, where some energy savings can still be achieved because the EDFAs that are not used can be set in sleep mode. More details on how the WPA-LR strategy works are available in [6].

B. Average Maximum Allowable Lifetime Decrease

Once WPA-LR is applied to a network in operation, different energy savings can be achieved, as a function of the load. For each one of these energy saving levels, it is then possible to compute an average value of $d_{\max}$ (i.e., $D_{\max}$) over all the EDFAs in the network. Figure 2 shows $D_{\max}$ in the COST239 network as a function of traffic load for the WPA-LR strategy with various values of α. $D_{\max}$ represents a boundary condition between the overall OPEX savings and losses. Let us define D as the average lifetime decrease of all the EDFAs in the network at a specific load. If applying WPA-LR results in average lifetime decrease values that are lower than the maximum allowed (i.e., $D < D_{\max}$), then WPA-LR will achieve an overall OPEX reduction. Otherwise, the WPA-LR will lead to an overall OPEX loss.

From Fig. 2 it can be noticed that $D_{\max}$ decreases with increasing traffic load (i.e., when there are lower chances to save energy by putting EDFAs in sleep mode). As expected, the $D_{\max}$ values for WPA-LR are higher with lower values of α, i.e., when WPA-LR makes more energy efficient routing choices. The highest values of $D_{\max}$ are obtained with WPA-LR where $\alpha \approx 0$, i.e., when energy savings are maximized, while the lowest curve of $D_{\max}$ corresponds to the $\alpha = 1$ (i.e., SP) case, when no green routing decisions are made.

C. Lifetime Decrease due to an Increased Fiber Link Occupancy

This section evaluates the impact on the EDFA lifetime caused by an increase of the fiber link occupancy as a result of the use the WPA-LR strategy.

Figure 3 presents two sets of graphs. The first set shows the normalized D (i.e., D') as a function of the traffic load in the COST239 network for different values of α ($\alpha < 1$). D' is

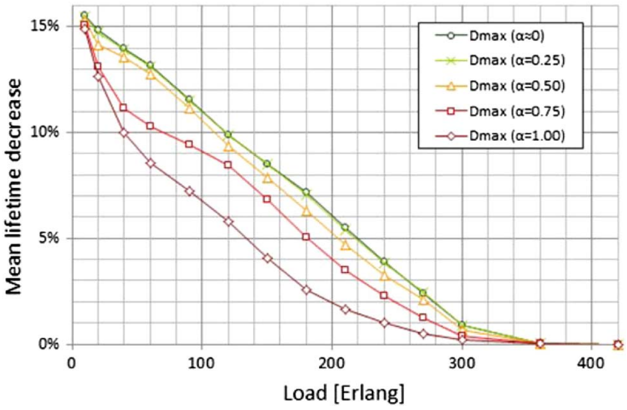

Fig. 2. $D_{\max}$ using WPA-LR with different values of α (COST239).

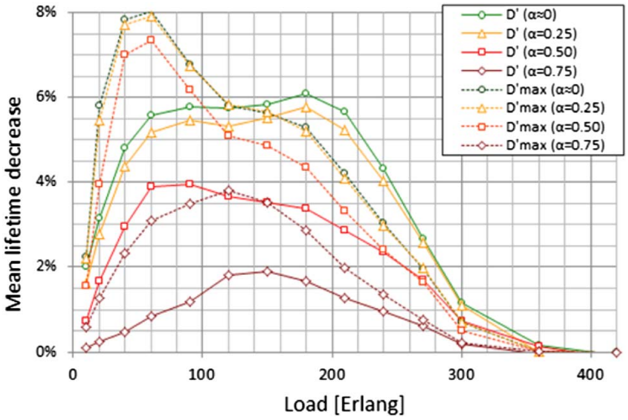

Fig. 3. Normalized D (D') and normalized $D_{\max}$ ($D'_{\max}$) for WPA-LR with different values of α (COST239).

computed considering only the effect of the increased fiber link occupancy and is normalized by the values obtained when $\alpha = 1$ (i.e., SP). For benchmarking purposes, the second set of graphs presents the normalized $D_{\max}$ (i.e., $D'_{\max}$) for a number of values of $\alpha < 1$. Also in this case, $D'_{\max}$ is normalized by the values obtained when $\alpha = 1$ (i.e., SP). From Fig. 3 it can be noticed that, for all values of α, the trend of the curves representing D' is similar to the ones of $D'_{\max}$. In fact, a high $D'_{\max}$ means higher achievable energy savings. On the other hand, better savings also means fiber links in the network that are on average more loaded and more prone to a lifetime reduction.

The figure also shows that, in the most aggressive energy saving case ($\alpha \approx 0$) and for traffic loads >120 Erlangs, D' is higher than $D'_{\max}$. With less aggressive energy saving approaches (e.g., $\alpha = 0.5$) and for traffic loads <120 Erlangs, D' is at least 50% lower than $D'_{\max}$.

These results suggest that, even if the WPA-LR algorithm is configured to offer high energy saving, there are some traffic conditions (>120 Erlangs) in which an increased average fiber link occupancy causes the normalized lifetime decrease D' to be larger than the boundary condition set by $D'_{\max}$. The WPA-LR configured for less aggressive energy savings (e.g., $\alpha = 0.5$) will be more beneficial in terms of lower reliability performance degradation, and may allow for an overall cost saving.

D. Lifetime Decrease due to On/Sleep Switching

This section evaluates the impact that on/sleep cycles have on the EDFA lifetime. The values of the frequency and duration of the sleep cycles are collected by simulating the WPA-LR algorithm for different values of α in the COST239 topology. During these simulations it was assumed that the average holding time of a connection request is equal to 6 h. We also performed a few experiments with different values of the holding time and noticed that it does not affect the validity of our general conclusions. The impact of on/sleep switching on the EDFA lifetime is calculated using both the Norris–Lanzberg and the Arrhenius acceleration factor formulas (see Subsection II.A). The combined overall acceleration factor is obtained by multiplying the results achieved with the two formulas. The resulting reliability performance impact (i.e., D) is then computed accordingly.

To calculate the Norris–Lanzberg acceleration factor, it was assumed that the reference case is represented by a regular on/off switching maintenance cycle. The test condition, on the other hand, includes, in addition to the maintenance cycles, the on/sleep cycles as a result of the WPA-LR strategy with different values of α. Several on/off switching frequencies for the reference case are considered i.e., one cycle per day (cpd), per week (cpw), per month (cpm), and per year (cpy). Although, the 1 cpy and 1 cpd reference maintenance frequencies may not be realistic, they are considered to show in which way D depends on the maintenance strategy. To calculate the Arrhenius acceleration factor, it is assumed that the EDFA operational temperature (T_r) is 40°C and the temperature in sleep mode (T_s) is 25°C on average.

Figure 4 shows both D and $D_{\max}$ as a function of load using WPA-LR with $\alpha = 1$, (SP). Different maintenance frequencies are compared and it can be seen that, in all cases, the lifetime of the EDFA significantly decreases when on/sleep switching is applied. This is because temperature cycling has a much higher (and negative) impact on the reliability performance than the positive effect brought by a lowered operating temperature. As expected, the reliability performance of an EDFA is less impacted (lower lifetime decrease) when the maintenance cycles are done more frequently.

When a more aggressive energy saving strategy is applied, i.e., WPA-LR with $\alpha < 1$, the frequency of the on/sleep cycles can be expected to be lower because, with these values of α, WPA-LR tends to reuse as much as possible fiber links that are already operational. Thus, the reliability performance degradation for WPA-LR with $\alpha \approx 0$ should be lower than for WPA-LR with $\alpha = 1$, (SP). This intuition is confirmed by looking at Fig. 5, which presents D assuming one maintenance cpw for the reference case. The values in the figure include the impact on reliability performance due to the on/sleep cycling, a low operational temperature in sleep mode, and an increased fiber link occupancy level.

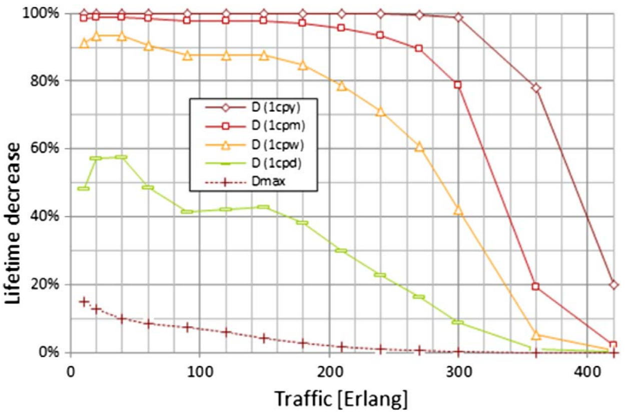

Fig. 4. D and $D_{\max}$ of EDFA caused by on/sleep switching for WPA-LR with $\alpha = 1$ (COST239).

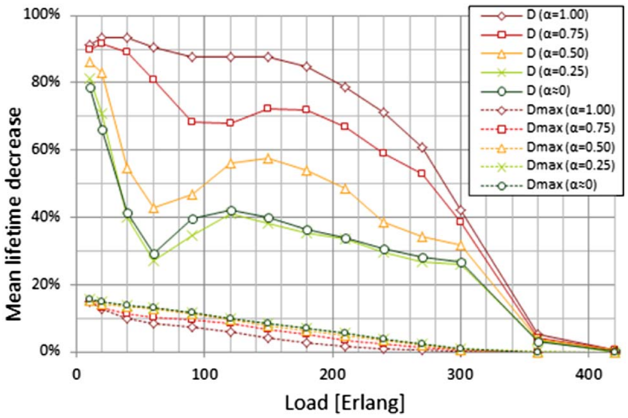

Fig. 5. D and $D_{\max}$ of EDFA caused by on/sleep switching for WPA-LR with different values of α, assuming a maintenance cycle of once a week (COST239).

It can be seen that D is still much higher than $D_{\max}$ for every value of α. One can notice that the curve of D for WPA-LR with $\alpha \approx 0$ reaches a local minimum at a traffic load of 60 Erlangs. This represents the condition when WPA-LR with $\alpha \approx 0$ offers the highest energy savings compared to WPA-LR with $\alpha = 1$, (SP) (see Fig. 3); i.e., WPA-LR routes use fiber links resources in the most energy efficient way and, as a result, the on/sleep switching is kept to a minimum.

In summary it can be concluded that the overall network OPEX may increase as a consequence of applying a green strategy (i.e., WPA-LR) since the negative impact of both thermal cycling and fiber link occupancy on the reliability performance of EDFAs is in many cases higher than the benefit achieved by the energy saving mechanisms.

E. Results for NSFNET Topology

Simulations for the NSFNET network were performed, as well, to validate the findings obtained for the COST239 network considering a different scenario. The range of the load values is chosen not to exceed 10% blocking probability, the same settings used for the COST239 network.

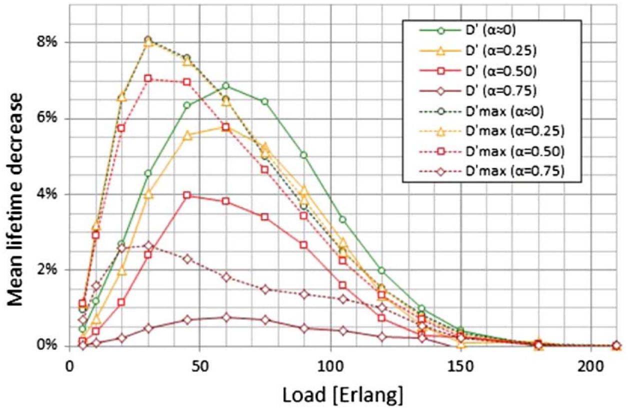

Fig. 6. D' and $D'_{\max}$ for WPA-LR with different values of α (NSFNET).

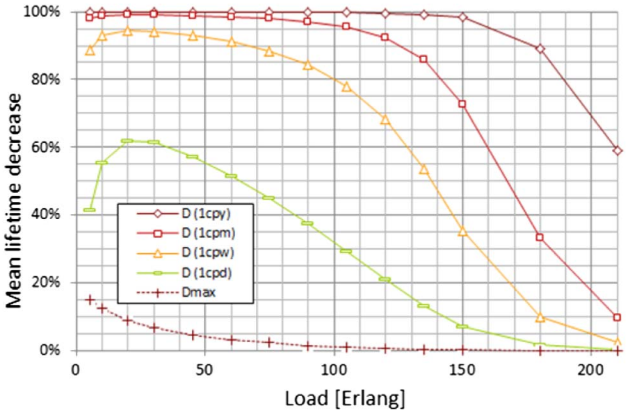

Fig. 7. D and $D_{\max}$ of EDFA caused by on/sleep switching for WPA-LR with $\alpha = 1$ (NSFNET).

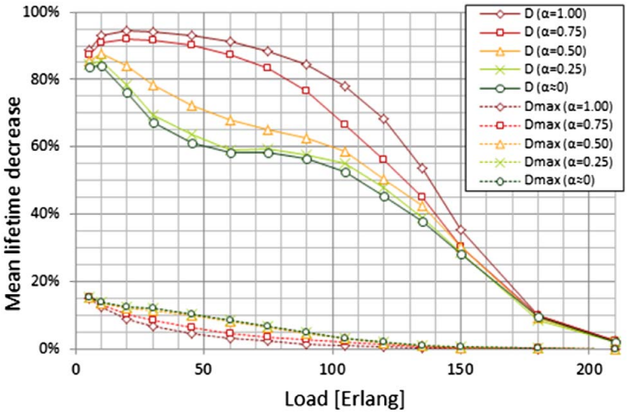

Fig. 8. D and $D_{\max}$ of EDFA caused by on/sleep switching for WPA-LR with different values of α, assuming a maintenance cycle of once a week (NSFNET).

Figures 6–8 show the results for the NSFNET, which exhibit trends similar to those in the COST239 case. However, there are some differences. First, the peaks for energy savings and reliability performance decrease occur at lower traffic loads. This can be explained by the lower average nodal degree of the NSFNET network compared to COST239, resulting in less routing options to establish connection requests. Second, the impact on the EDFA lifetime (D) is higher in the NSFNET network topology (see Fig. 6). This is because, in the NSFNET, fiber links are on average longer and require more EDFAs per link, which consequently increases the negative impact on reliability performance, especially when the average fiber link occupancy increases.

V. CONCLUSIONS

This paper discussed how energy efficient strategies can impact the lifetime of a device by investigating the physical phenomena triggered by frequent on/sleep cycles. Two metrics were introduced, namely, the *maximum allowable* (mean) *lifetime decrease* ($d_{\max}$) and the *minimum time a device should be kept off to save enough energy to compensate for the reparation costs of a single failure* ($t^{\mathrm{off}}_{\min}$). These two parameters were used to assess the reliability performance of a number of components in optical core networks. Among them, EDFAs were found to present the lowest $d_{\max}$ and the highest $t^{\mathrm{off}}_{\min}$ values. This means that EDFAs can be considered among the devices that are most susceptible to possible reliability performance degradation in the presence of energy saving strategies. This also implies that green routing and wavelength assignment algorithms leveraging on EDFAs in sleep mode could severely affect the EDFA reliability performance. To verify this, this paper presented a study where an energy saving algorithm based on setting EDFAs in sleep mode (i.e., WPA-LR) was evaluated. The results showed that the average EDFA lifetime decrease (D) is significantly higher than the maximum allowable lifetime decrease ($D_{\max}$). This is caused mainly by high average fiber link occupancy and by frequent on/sleep cycles. In this condition, the extra reparation costs caused by reliability performance degradation of EDFAs will be higher than reduction of the energy bill. In summary, it can be concluded that the use of energy efficient routing algorithms based on setting EDFAs in sleep mode may not always be appropriate.

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