Lifetime-Aware Provisioning in Green Optical Backbone Networks

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Abstract: We present a framework able to limit the device lifetime degradation in optical backbone networks using sleep-mode-based green strategies. Results show that our approach manages the lifetime while not compromising significantly the energy saving performance.

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1. Introduction

Green optical networking has gained significant importance and received a lot of attention in recent years [1]. One of the most promising solutions proposed so far is based on setting unused network devices into Sleep Mode (SM). This approach allows to exploit the day/night variations of optical backbone networks traffic and to put into SM a number of devices during off peaks hours. However, one of the main drawbacks of SM-based green strategies is the impact that SM operations have on the lifetime of network devices [2]. In particular, setting too frequently a device into SM may decrease its lifetime, due to the fact that network devices are designed to be always powered on. With shorter lifetime the reparation and replacement costs of a device are likely to increase, running the risk to possibly canceling the savings enabled by energy-aware policies.

The goal of this work is to investigate the optimal tradeoff between energy saving levels and lifetime variations of optical devices in backbone networks. The paper focuses on energy saving strategies based on setting Optical Line Amplifiers (OLAs) into SM, but the framework can be applied to any other relevant type of device. When an OLA is put into SM, its lifetime tends to increase w.r.t the full power case, thanks to a reduction in the operating temperature of the device. However, when an OLA changes its power state too frequently (e.g., to/from SM), its lifetime is reduced due to the temperature variations triggered by the power status changes [3]. When a specific OLA is not in use, it becomes then crucial to understand whether or not it is worth to set it into SM to save energy w.r.t. the possible OLA lifetime decrease it might incur. This problem is formulated in the paper as a MILP (Mixed Integer Linear Programming) model, and solved using a realistic traffic scenario. Results from the proposed lifetime aware provisioning strategy show that it is possible to limit the lifetime decrease of OLAs while still being able to achieve very good energy savings results.

2. OLA Lifetime Model

We consider the lifetime model presented in [2]. Rather than working directly with lifetimes, we adopt a metric called (lifetime) *acceleration factor* (AF). The AF is defined as the ratio between the mean lifetime when an OLA is always kept at full power (γ^{on}), and the lifetime when an OLA is periodically set into SM (γ^{tot}). The AF can be expressed as

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

where $AF^{sleep} \in (0,1)$ is a HardWare (HW) parameter defining the AF experienced by an OLA when it is always kept in SM (by neglecting the effects of power state transitions), θ is the total amount of time spent by an OLA in SM, T is the total period of time under consideration, $\chi > 0$ is a HW parameter representing the AF variations caused by a single full power - SM cycle, and $\frac{c}{2}$ is the total number of full power - SM cycles an OLA goes through (where each cycle is composed of two transitions, full power/SM and SM/full power). If AF > 1, the OLA lifetime is decreased compared to the full power case. We can see that the lifetime variation is influenced by the HW parameters (AF^{sleep} and χ) that depend on the components used to build the OLA, and by the parameters related to the SM policy (θ and c) whose impact can be limited by wisely choosing the length and frequency of the full power/SM cycles, i.e., with a lifetime-aware SM strategy as the one described in the next section.

Table 1. Main Notation

	Symbol	Unit	Description
Input Parameters	V	-	Set of nodes
	E	-	Set of physical links, each link $(i,j) \in E$ from node $i \in V$ to node $j \in V$
	K_{ij}	-	Set of fiber links on the physical link $(i,j) \in E$
	OLA_{ijk}	-	Set of OLAs installed at fiber link $(i,j,k), (i,j) \in E, k \in K_{ij}$
	X_{ijk}	[units]	1 if the fiber link (i,j,k) was used during the previous time period, and 0 otherwise
	W_{ijk}	[units]	Total number of wavelengths for fiber link (i,j,k)
	C_{ijk}	[units]	Total number of power state transitions for fiber link (i,j,k) up to previous time period
	Θ_{ijk}	[h]	Total time in SM for fiber link (i,j,k) up to previous time period
	t^{sd}	[units]	Number of wavelengths required to accommodate a lightpath from node s to node d $(s,d \in V)$ during current time period
	δ_t	[h]	Time duration of current time period
	AF^{sleep}_{ijkq}	[units]	AF when the OLA q on fiber link (i,j,k) is in SM
	χ_{ijkq}	[1/h]	HW parameter accounting for the AF increase due to power state transitions for OLA q on fiber link (i,j,k)
	T	[h]	Total observation time
Variables	f^{sd}_{ijk}	[units]	Number of used wavelengths for the lightpath from node s to node d routed through fiber link (i,j,k)
	f_{ijk}	[units]	Total number of used wavelengths on fiber link (i,j,k)
	x_{ijk}	[units]	1 if fiber link (i,j,k) is used during current time period, 0 otherwise
	z_{ijk}	[units]	1 if fiber link (i,j,k) experiences a power state transition between the current time period and the previous one, 0 otherwise
	c_{ijk}	[units]	Total number of power state transitions of fiber link (i,j,k) up to current time period
	θ_{ijk}	[h]	Total time in SM for fiber link (i,j,k) up to current time period
	AF_{ijkq}	[units]	Total AF of OLA q on fiber link (i,j,k)

3. Problem Modeling

We formulate a MILP model referred to as Least Acceleration Factor (LAF). Given a physical network topology and a set of traffic matrices (TMs) (one for each time period under exam) LAF returns the logical topology realization accommodating all the lightpath requests from the traffic matrix in each period. This is achieved by minimizing the average value of AF over all the OLAs in the network (2) for each time period. The notation used in this model is presented in Table 1. In particular, we take power state decisions considering only the knowledge of the TM of current time period and the past SM decisions,[1] without assuming the future traffic awareness.

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

Subject to

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

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

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

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

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

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

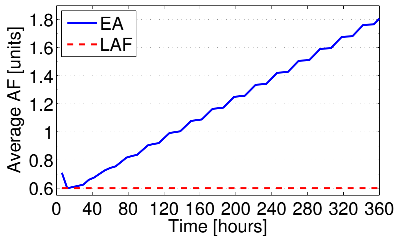
$$AF_{ijkq} = \left[1 - \left(1 - AF^{sleep}_{ijkq}\right)\frac{\theta_{ijk}}{T} + \chi_{ijkq}\frac{c_{ijk}}{2}\right], \quad \forall (i,j) \in E, \forall k \in K_{ij}, \forall q \in OLA_{ijk} \tag{9}$$

Constraint (3) ensures the flow conservation for all the demands. Constraint (4) counts the total number of wavelengths used on fiber link (i,j,k) by all the traffic demands. Constraint (5) ensures that on fiber link (i,j,k) one cannot use more wavelength than the maximum, and it also sets the power state of the OLAs on fiber link (i.e., decides the value of variable x_{ijk}). Constraint (6) computes the number of transitions (0 or 1) of the OLAs on fiber link (i,j,k) between the current time period and the previous one. Constraints (7) and (8) count, for a given fiber link (i,j,k), the total number of power state transitions and the total time spent in SM up to current time period, respectively. Constraint (9) calculates the AF value for each OLA up to current time period.

4. Case Study

We evaluate the performance of LAF in terms of average AF over all the OLAs in the network and in terms of energy consumption. We adopt as input the physical topology of the Abilene network derived from [5]. In particular, the

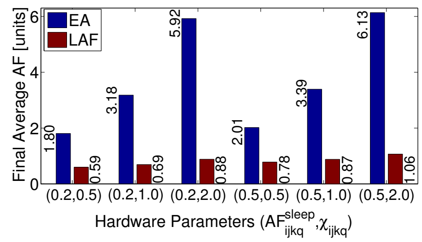
[1] For the TM of the first time period we assume to start with all the OLAs in SM.



(a) Average AF ($AF_{ijkq}^{sleep} = 0.2$ and $\chi_{ijkq} = 0.5$)

	EA	LAF (AF_{ijkq}^{sleep} = 0.2 and $\chi_{ijkq} = 0.5$)
Energy Consumption [kWh]	2967.84	2967.84
Energy Savings [%]	62	62

(b) Energy Comparison



(c) Final average AF (after 15 days, varied HW parameters)

Fig. 1. AF and energy for the Abilene-based topology using EA and LAF strategies.

physical topology corresponds to a network design results based on the maximum value of the IP traffic measured on the Abilene network over the period 01–31/07/2004, scaled up to mimic current traffic demands [5]. In this work we consider the day/night traffic variations over a period of 15 days. During each day we assume to have a high-traffic between 06:00 am and 11:45 pm and a low-traffic period between 12:00 am and 05:45 am. The choice of the lengths of the low and high-traffic periods is dictated by the relatively long times needed to power on an OLA, full network operation targeted during a day, and energy saving targeted at night. The set of lightpaths to be established during each period is obtained by considering the logical topologies derived from [6]. A custom event driven simulator is used to simulate a network subject to dynamic traffic according to the scenario described above. The MILP model presented in Section 3 is solved for each traffic period and the resulting OLAs power states on the links are applied to the network. We assume that all network nodes have full wavelength conversion capability, each fiber link (i, j, k) has capacity of 80 wavelengths, OLAs are placed every 80 km, and each OLA consumes 18 Watts [2]. Finally, we assume the same HW parameters AF_{ijkq}^{sleep} and χ_{ijkq} for all the OLAs.

For benchmarking purposes, we compare LAF with the results of the Energy-Aware (EA) ILP model [4]. Fig. 1(a) presents the average AF over the OLAs in the network as a result of using LAF and EA where $AF_{ijkq}^{sleep} = 0.2$ and $\chi_{ijkq} = 0.5$ [1/h]. The EA model experiences a maximum lifetime decrease of 80% w.r.t. the case in which the OLAs are always kept at full power. On the contrary, the average AF values computed as a result of LAF are equal to 0.6 after 15 days, i.e., a lifetime increase of 40%. This is because even if LAF and EA use, most of the time, the same route to accommodate the low- and high-traffic requests, LAF tends to limit the power state transitions on each fiber link, i.e., it chooses to put a fiber link into SM only when past decisions (in terms of SM states) allows for it. On the other hand EA decides on the power status of a fiber link regardless of its past SM states. Interestingly, LAF is able to save the same amount of energy compared to EA, as reported in Fig 1(b). To give more insight, Fig. 1(c) shows the value of AF after the 15-day period as a function of the variations of HW parameters AF_{ijkq}^{sleep} and χ_{ijkq}. When the value of AF_{ijkq}^{sleep} is increased, the gain for putting OLAs into SM is reduced. Consequently, the AF tends to increase. At the same time, when χ_{ijkq} is increased, the impact of power state transitions is higher. While the EA tends to notably increase the AF when the HW parameters are increased, our approach is able to limit this lifetime degradation.

5. Conclusions

We have proposed a framework to optimize the OLA lifetime in green optical networks. This paper is (to the best of our knowledge) the first one to conduct this type of analysis. It is shown that the proposed method, called LAF, is able to efficiently avoid the OLA lifetime decrease and save energy by putting selected OLAs into SM during low-traffic periods. As future work, we will consider the problem of maximizing the electricity savings while minimizing the reparation costs driven by lifetime variation. Additionally, we plan to perform a measurement analysis of the HW parameters impacting the lifetime in an operator network.

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