Energy Saving in Access Networks: Gain or Loss from the Cost Perspective?

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ABSTRACT
Energy consumption in telecommunication networks has become a significant problem during the last few years. Many energy efficient mechanisms have been proposed and evaluated with respect to their impact on the overall network performance (*e.g.*, delay, blocking probability, quality of transmission). Most of these mechanisms are based on the *sleep mode* functionality, *i.e.*, a "*low power"* state of network devices that can be utilized in low traffic conditions. On the other hand, a frequent switching between a working and a sleeping state may increase the probability of failures in a device, which in turn makes the operational cost related to fault reparation higher. This paper discusses how sleep mode-based energy saving mechanisms can impact the reliability performance of network equipment by pointing out several physical phenomena that may lead to an increase of the failure rate. In order to quantify such effects we propose a methodology that estimates to what extent energy savings can be maximized without exceeding the extra reparation cost caused by the degradation of the reliability performance of network equipment due to frequent switching on and off. We perform a number of simulative studies focused on an optical access segment and show that the cost saved by reducing the energy consumption (*i.e.*, as the result of a power efficient mechanism) may be easily overcome by the extra expenses related to reparation of network equipment and service interruption for business users.

Keywords: Energy efficiency, sleep mode, reliability, access networks, passive optical network (PON), cost analysis

1. INTRODUCTION

The worldwide energy consumption is rising. The information and communication Technology (ICT) sector amounts to 8% of the total energy consumption worldwide and communication networks are responsible for 30% of energy consumed by ICT [1]. These numbers translate into huge energy costs to run networks. On the other hand, the access network segment typically experiences high traffic variations with a low average utilization of network resources. It is shown that the current average utilization of access network devices is lower than 15% [2] making it important to improve efficiency of use of the access energy resources. With respect to this problem a number of power efficient mechanisms have been proposed in the literature [3]-[5], and the topic of energy efficiency has also been addressed in standardization bodies [6]. Most of the proposed schemes try to adapt device's energy consumption to the traffic conditions using the so called *sleep mode* functionality, *i.e.* switch the device to a low-power (sleep) mode when the traffic is low.

The introduction of these power efficient schemes is beneficial in terms of a reduced energy consumption, but may negatively impact the overall network performance. These important tradeoffs has been addressed in the literature in the case of both core and access technologies, where a number of works [5], and [7]-[10], tried to find the best way to mitigate the performance degradation while still optimizing energy cost savings.

However, a frequent switching between a working and a sleep state may also increase the risk for equipment failure, which in turn translates to higher operational expenditures in terms of an additional reparation cost and potential service interruption penalties. We are again in the presence of a tradeoff between the gain associated with the introduction of power efficient schemes and the potential losses one has to face to maintain devices with an increased failure rate. This is particularly true in the access segment where both the number of devices (*i.e.*, the number of end users) and of on/off transitions due to traffic fluctuations are potentially higher than in the metro and core part.

This paper focuses specifically on the reliability aspects of energy efficient schemes. To the best of our knowledge this is the first work that addresses this problem in communication networks. We are trying to assess the relation between the effects of an energy efficient scheme on the equipment reliability performance by considering a number of physical phenomena together with their models. We propose a methodology to quantify to what extent the energy saved as a result of a specific scheme can be maximized while keeping the extra reparation costs below the potential reduction of the electricity bill.

A number of use cases are identified for an access segment scenario based on wavelength division multiplexing (WDM) - passive optical networks (PON), where both residential and business users are considered. With the help of the proposed methodology we show that it is indeed very important to consider the equipment reliability performance degradation. This is particularly true in those scenarios where the cost for reparation and service disruption is so high that even small variations in the device failure rate may potentially overcome possible saving coming from the energy efficient scheme under exam.

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2. ENERGY EFFICIENCY VS. RELIABILITY PERFORMANCE

Most of the energy efficient schemes for access networks [2], [3] are based on putting devices in sleep mode, *i.e.*, switching on/off network equipment according to the traffic variation. There are good reasons to expect that this frequent switching between an "on" and a "sleep" state could have a negative impact on the reliability performance of the devices involved. The reason behind this intuition is the following.

An experimental evaluation was conducted for compact fluorescent lamps (CFLs) from different manufacturers [11]. It was observed that the lifetime of a lamp could decrease up to 97% when the on/off switching frequency raises from 7.2 to 270 cycles per day (see Fig. 1). Following the same reasoning it could be expected that the introduction of sleep mode functionality in communication network devices will have the same negative impact on their reliability performance. But what are the physical reasons behind this degradation?

On/off switching affects the conditions in which the device operates, in particular its temperature [12]. There are several models that describe the relation between the temperature of a device and its reliability performance. One of the models that is utilized in accelerated reliability tests of components is called the Arrhenius law [13]. It refers to an acceleration factor that defines how much the failure rate of a device could increase if it operated at a temperature higher than a reference temperature. For example, the lifetime of an electrolytic capacitor is approximately halved each time the temperature raises with 10 degrees Celsius. If the Arrhenius acceleration factor was the only parameter considered, energy efficient schemes would have a positive impact on the device reliability performance, because a device in a sleep mode typically has lower temperature than in full working conditions. However, there are also other phenomena that need to be considered and which can negatively impact the reliability performance.

Temperature changes, for example, may cause material expansion. Different materials within the same component have different coefficients of temperature expansion (CTE) and could suffer strain and fatigue with varying temperature conditions, especially if this happens in a cyclic way. In fact, this is the case for many electronic devices. The Coffin–Manson model [14], [15] describes the effects of material fatigue induced by cyclic thermal stress on a component and is used to predict the number of temperature cycles during the component lifetime. In this case, the frequency of the temperature changes plays an important role because the more often a device is put into sleep mode the shorter its lifetime will be. There are many other models specific for electronic equipment (*e.g.*, Engelmeier [16], Norris-Lanzberg [17]) that introduce additional factors (*e.g.*, solder dimensions, its chemical characteristics, dwell time) into a reliability performance impact model. Their common underlying factor is their dependence on the frequency of the temperature cycles, *i.e.*, with higher frequency the estimated lifetime is expected to be shorter. One could argue that on/off switching (*i.e.*, power cycling) in a sleep mode based scheme produces a localized heating in the device (Joule heating) and that the resulting temperature variation may not be uniformly distributed over the whole device. On the other hand [18] and [19] confirm that the fast local temperature changes caused by power cycling (that can be up to 100 times faster [20] than the thermal cycling) also negatively impacts reliability performance.

In summary, temperature and temperature variations are the two most direct effects introduced by a power efficient scheme that can possibly impact the device's reliability performance. There are also other indirect factors that can be considered such as corrosion (*e.g.*, Peck's power law for temperature and humidity combined effects), humidity, and vibration. For instance, temperature variations due to frequent on/off switching may result in water condensation that in turn can cause corrosion. A combination of all these effects (direct and indirect) may degrade the reliability performance of the components involved and, consequently, increase the cost related to the failure management. Therefore, it is important to assess such impact from the cost perspective.

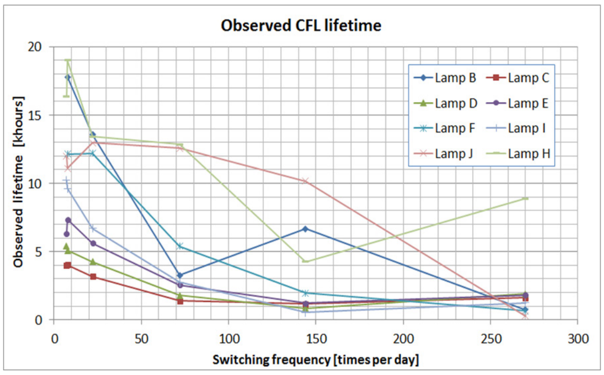

Figure 1. CFL lifetime.

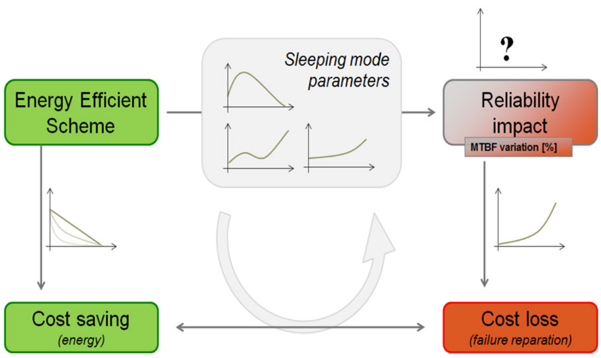

Figure 2. Cost analysis.

3. COST ANALYSIS FRAMEWORK

From the cost perspective, the analysis of the impact of energy saving mechanisms on the reliability performance can be divided into two parts. The first one considers the gains related to the reduction of the energy consumption while the second part estimates the additional fault management cost associated with the reliability performance degradation of the device. Once the results from both analyses are combined, it is possible to provide an answer to whether a given sleep mode based scheme is beneficial from the overall cost perspective.

Trying to assess the impact of a given energy efficient scheme on the reliability performance is a complex task (see Section 2), where different effects related to material, solder layout design, environment, *etc*., must be taken into account in addition to sleep mode functionality. Therefore, it's difficult to get a general answer to the problem. Instead we identify the maximum allowable negative impact of a sleep mode based power efficient scheme on the equipment reliability performance that would still give the cost savings, *i.e.*, where the gain from the reduction of energy consumption is higher than the cost related to the reliability performance degradation of the network equipment involved.

The block diagram shown in Fig. 2 presents the main steps in our study, which are described in detail below. The impact on the reliability performance is measured in terms of variation of the mean time between failures (MTBF) of a device. MTBF is the sum of the mean lifetime (referred to as the mean time to failure (MTTF)) and the mean time to repair (MTTR). In this study MTTR is assumed to be constant, therefore the MTBF variations are only due to changes of the MTTF. If the maximum allowable value of MTBF variation is relatively high, it means that significant energy savings can be achieved without considering the impact on reliability performance. If, on the other hand, the maximum allowable MTBF variation is low, there is a risk that a given energy efficient scheme may not be beneficial from an overall cost perspective.

Energy related cost saving

In any power efficient scheme based on the sleep mode concept, the energy saved over a period of time is a function of how long a device stays asleep, which in turn strongly depends on the traffic conditions (with high traffic is not possible to go to sleep and consequently no energy can be saved). For this reason energy saving is often presented in the form of an energy profile, which shows the device's normalized energy consumption in function of the traffic load [21], (see *e.g*., Fig. 3). Given the device's energy profile it is then possible to compute the energy consumption, still as a function of traffic load. Then using the information about the energy price it is also possible to calculate the energy related cost saving per year (noted hereafter as $\Delta Cost_{energy,}$ which is also in function of the traffic load).

Failure related loss caused by MTBF variation

In the proposed methodology the impact on the equipment reliability performance is measured in terms of MTBF variation. We introduce the parameter v_{MTBF}, which varies in the range [0, 1). The $v_{MTBF} = 0$ corresponds to no impact on MTBF, on the other hand the high value of v_{MTBF} (close to 1) refers to a large decrease of MTBF. The new value of MTBF (denoted hereafter as $MTBF_{new}$) can be calculated in the following way:

$$MTBF_{new} = MTBF_{ref} * (1 - v_{MTBF}). \tag{1}$$

$MTBF_{ref}$ is the MTBF of a device operating without any energy efficient scheme implemented. The cost related to failure reparations (denoted hereafter as $Cost_{failure}$) can be calculated as:

$$Cost_{failure} = (operation\_period\,/\,MTBF_{ref}) * failure\_cost. \tag{2}$$

The *operation_period* is the considered period of time for our cost analysis; in our case it is equal to one year to be comparable with energy related cost saving (*i.e.*, $\Delta Cost_{energy}$). The *failure_cost* represents the average cost to repair one failure and it includes: reparation manpower, travel, and also a penalty to compensate for the service interruption, typically used for business customers only. We calculate the extra cost caused by MTBF variation (denoted hereafter as $\Delta Cost_{failure}$) as the difference between the fault management cost in the case when an energy saving mode is applied (*i.e.* $Cost_{failure}$ with $MTBF_{new}$) and the cost when no energy efficient scheme is considered (*i.e.*, $Cost_{failure}$ with $MTBF_{ref}$). Therefore, $\Delta Cost_{failure}$ can be expressed by the following equation:

$$\Delta Cost_{failure} = Cost_{failure} * v_{MTBF} / (1 - v_{MTBF}). \tag{3}$$

Maximum allowed MTBF variation

The value of the maximum allowable MTBF variation (denoted hereafter as V_{MTBF}) is calculated when the energy related saving completely compensates the failure related loss *i.e.*, $\Delta Cost_{failure} = \Delta Cost_{energy}$. In such boundary condition it can be calculated in the following way:

$$V_{MTBF} = \Delta Cost_{energy} / (\Delta Cost_{energy} + Cost_{failure}). \tag{4}$$

As the $\Delta Cost_{energy}$ is computed as a function of traffic load the V_{MTBF} is also traffic dependent.

4. CASE STUDIES

This section presents an assessment of the proposed methodology. A number of scenarios are considered, as explained next. The study focuses on WDM-PON based access networks. They are in fact considered as the most promising candidates for the optical future access networks both in residential and business areas. In PON the active devices are located at the customer premises (referred to as optical network units (ONUs)) and in the central office where the optical line terminal (OLT) is managed by the operator. The case studies under exam are differentiated based on the customer profile (*i.e.*, residential or business) and on the location of the failure. For residential customers, it is assumed that only the ONUs are switched on/off to save energy. As a result only ONUs might be affected by the energy saving mechanisms. On the other hand, for business customers, two different cases are considered. In the first one, only the ONUs are switched on/off to save power. If an ONU malfunctions, only one customer at a time is affected, similarly to the residential case. However, since we are considering business costumers the *failure_cost* (see equation (2)) parameter includes an additional penalty for service interruption. In the second case it is assumed that only the OLT is switched on/off in order to save energy. Since the OLT serves more than one customer, its failure has a relatively larger impact compared to the failure of an ONU. In this work it is assumed to have one OLT that is connected to 80 business customers. All of them are out of service at the same time if the OLT fails. Table 1 provides a number of details about the scenarios. The costs corresponding to failures are calculated based on the data presented in Table 2.

Table 1. Scenarios.

Scenario name	**Description**	**Mean travel and reparation times as well as persons involved in the process**	**Penalty**	**Failure_cost** [USD]	**MTBF** [h]
Residential (*ONU*)	Sleep mode applied at ONU side ONU failure affects one customer	Mean travel time – 2h & 1 person Mean reparation time – 1h & 1 person	n/a	570	236 842 [25]
Business (*ONU*)	Sleep mode applied at ONU side ONU failure affects one customer	Mean travel time – 2h & 1 person Mean reparation time – 1h & 1 person	2h & 1 customer	2 970	236 842 [25]
Business (*OLT*)	Sleep mode applied at OLT side OLT failure affects 80 customers	No travel time Mean reparation time – 2h & 1 person	2h & 80 customers	192 380	214 286 [25]

5. ENERGY CALCULATION ASSUMPTIONS

For all three scenarios presented in the previous section (one for residential and two for business users) we consider the power saving scheme proposed in [22], resulting in the energy profile function presented in Fig. 3. The value of cost of energy used in the simulation study, as well as the power consumption of an ONU/OLT in operational and sleep mode, in addition to other cost related parameters are presented in Table 2. The energy cost saving per customer per year ($\Delta Cost_{energy}$) is shown in Fig. 4.

Table 2. Cost calculation parameters.

Item	**Value**	**Unit**
Energy cost	0.27 [23]	USD/kWh
ONU's power On/Sleep	3.85 / 1.70 [24]	W per device
OLT's power On/Sleep	98 / 43.3 [25]	W per device
Personal cost	190 [25]	USD/(h*person)
Penalty cost	1 200 [25]	USD/(h*customer)

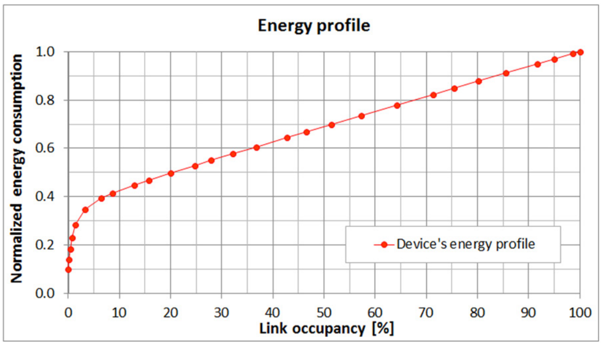

Figure 3. Energy profile.

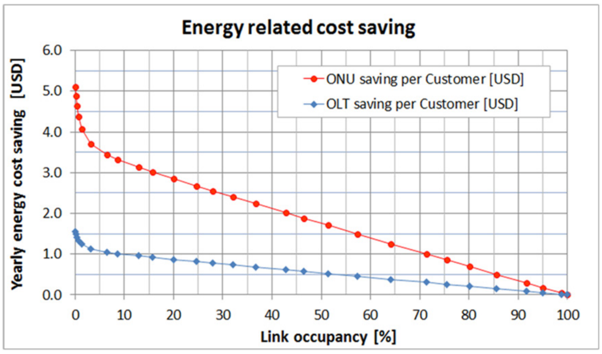

Figure 4. Energy related cost saving per customer per year in function of traffic.

6. RESULTS

The value of V_{MTBF} as a function of the traffic load is presented in Figs 5 and 6 for the residential and the two business scenarios, respectively. The value of V_{MTBF} decreases for increasing values of the traffic load in all three scenarios. This is because the energy saving become smaller for higher traffic loads and consequently failure related costs become less affordable. V_{MTBF} reaches its maximum value when the energy saving is maximized, *i.e.*, when the traffic load is minimal. On the other hand, in maximum load traffic conditions V_{MTBF} = 0% in all scenarios. This is because with such high traffic conditions device never enters the sleep mode, and without energy saving there is no room to afford any MTBF variations.

When looking at all three scenarios at the same time it is possible to notice that the value of V_{MTBF} is higher in the residential costumer scenario, where V_{MTBF} reaches up to 22.51%. Such big MTBF variation is possible because of the fairly low value of the *failure_cost* parameter, which does not include any penalty for service interruption. In fact in the business scenarios, where the value of *failure_cost* is higher, the V_{MTBF} is smaller than in the residential case. For the business ONU scenario, *i.e.*, when an ONU can malfunction, V_{MTBF} reaches values up to 5.28%. For the business OLT case, *i.e.*, when OLT can malfunction, the maximum V_{MTBF} value is even smaller and of 1.57%.

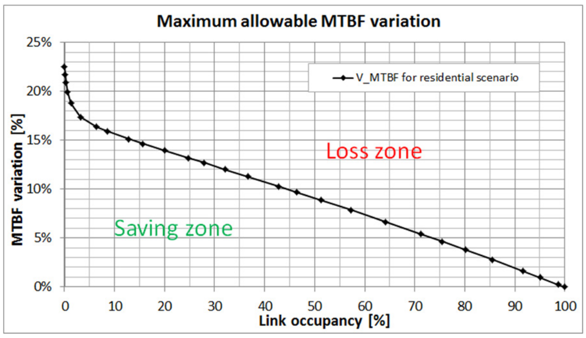

Figure 5. Residential customer scenario.

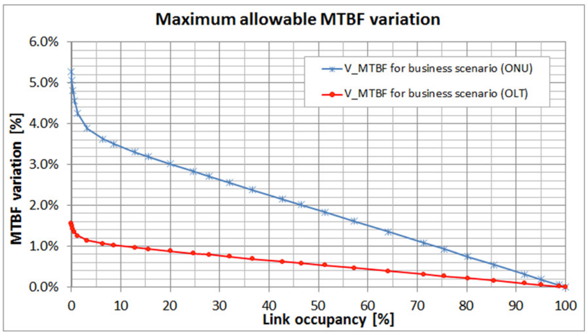

Figure 6. Business customer scenarios.

Since V_{MTBF} represents the value of v_{MTBF} such that $\Delta Cost_{failure} = \Delta Cost_{energy}$ it can also be seen as a value representing the boundary between the cost saving conditions (*i.e.*, values of $v_{MTBF} < V_{MTBF}$ represented on Fig. 5 as *Saving zone*) and the cost loss conditions (*i.e.*, values of $V_{MTBF} < v_{MTBF}$ represented on Fig. 5 as *Loss zone*). If a given power efficient scheme results in MTBF variation within the *Saving zone* for all traffic loads (referred to as link occupancy in Figs 3-6) than the scheme is really able to achieve an overall cost saving. However, as shown in Figs 5 and 6, the maximum allowable degradation of the reliability performance is strongly dependent on the traffic load, which is a consequence on the energy saving variation for different link occupancy conditions.

7. CONCLUSIONS

In this paper first we discussed how the lifetime of network devices could be negatively impacted by energy efficient strategies based on frequent on/off switching. In this regard several physical phenomena (*e.g.*, temperature changes) that could degrade the reliability performance of a device were highlighted. A methodology was proposed in order to quantify from the cost perspective to what extent energy saving can be beneficial over the possible extra reparation costs. The methodology was evaluated using a number of network scenarios based on WDM-PON where both residential and business customers were considered. The results show that for the case of residential customers the cost saving due to a power consumption reduction can easily compensate for possible extra reparation costs due to an increased number of the ONU failures at the customer premises. However this is not the case when business customers are involved, *i.e.*, the power saving are relatively small in comparison with the extra cost incurred for service interruption and for equipment reparation when an ONU fails. These considerations leave a limited space for the possible reliability performance degradation. Similar conclusion can be drawn in the case of a network device shared by many customers, *i.e.*, an OLT, where the energy saving may not bring sufficient cost benefits to compensate additional loss caused by reduced reliability performance level.

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