# Impacts of Energy Efficiency Features on Lifetime of Network Equipment

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***Abstract*—Energy efficiency features are being integrated in network protocols and management systems in order to make the infrastructure more sustainable and, at the same time, address the growing users' demand. Many of such features affect the network in different ways, thus yielding trade-offs. They can affect the reliability and availability of the network when they put devices or links into sleep mode, and they can affect the lifetime of the devices as a result of the new pattern of operation. This work discusses what needs to be evaluated when considering equipment lifetime, with respect to processor of network devices. We show that the new network management profile does affect the equipment lifetime negatively, in contradiction to what recent works seem to predict. We also present our ongoing research on how to calculate the trade-offs considering performance, availability, energy efficiency, and lifetime. These aspects must be taken into account in cost functions used to define the best network configuration. The key of our analysis and method relies on the understanding of thermal cycling and the power of using it in a predictive fashion.**

## I. Introduction

Projections show that Internet users will exceed two billions in 2015 and three billions in 2020 [1]. To cope with such a demand, the Network Service Providers (NSPs) have been announcing plans to enlarge the network infrastructure [2]. At the same time, the NSPs are concerned with global carbon emissions and the increasing energy consumption of operation [2], [3]. This way, considering the increasing energy expenses and carbon footprint of Information Technology (IT), many strategies have been proposed to reduce energy consumption in IT systems and networks. Since networks correspond to a significant part of IT energy expenses, various solutions of energy efficient networks are being proposed, from design related projects to network management systems [4]. Examples are demand-aware CPU frequency scaling, switch/router power mode adaptation, and energy-efficient traffic engineering [2], [5].

One of the main strategies involves putting devices to sleep according to traffic demand and to equipment power models, thus changing the network state. Such a procedure makes the energy consumption considerably lower, but leads to trade-offs on performance and reliability as stated in [6] and [7]. Also, turning devices on and off could affect the hardware lifetime. This way, how to measure the expected lifetime is an important discussion. By means of a probabilistic approach, lifetime estimations can be made, from which manufacturers can calculate the best deadline for warranties. The probabilistic apparatus typically used relies on exponential distributions, driven by a failure rate parameter.

Srinivasan et al. [8] state that the processor goes through two types of thermal cycles: *(a)* large thermal cycles, which occur at low frequency, such as powering up and down, or going into and coming back from standby mode, and *(b)* small cycles, which are much more frequent and are due to workload behavior or context switching. As a consequence of energy efficiency strategies, such as making use of different power states (e.g., sleep mode), the large thermal cycles, previously infrequent, become more frequent, thus motivating the analysis on possible impacts.

This work evaluates the impact of an operation that puts equipment into or off sleep mode with respect to lifetime. In this regard, the main proposal of this work is to study how energy efficient features of networks impact on devices lifetime considering the available references. We want to assess which network routing decision is the best with respect to different constraints: (i) power consumption reduction, mainly achieved through the sustainability techniques; (ii) cost, affected by the cost of acquisition, of power consumption and of the (iii) varying mean time to failure of different parts of the network. First, we show how energy efficiency strategies regarding sleep modes could affect the lifetime of network equipment during operation. After, we present our ongoing work related to quantifying the impacts in order to support the decision making process on how to save energy in the network.

The remainder of this paper is organized as follows. Section II provides the state-of-the-art related to failure rate and lifetime evaluation. Section III presents and discusses failure mechanisms of processors. Section IV points out the necessity of more work on understanding thermal cycling and shows how the knowledge of failure rate could be used in a predictive fashion. Section V discusses our ongoing work. Finally, other considerations are found in Section VI.

## II. Related Work

The work of Rosing et al. [9] is related to failure mechanisms. They proposed a Markov decision model to decide in which state (active or sleep mode) a device should be put in, considering memory, interconnects and processor. The decision is based on the power consumption and failure rate of each state. It does not cover the interaction between different devices. The evaluation method described by Srinivasan [8] utilizes a processor simulator (RAMP), which relies on another simulator (HotSpot), to perform temperature calculation. HotSpot receives as input the instructions executed during the simulation and provides to RAMP the temperature variations resulted from execution. RAMP then analyzes variations in

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MTTF (the Mean Time To Failure). HotSpot requires the processor architecture. RAMP requires constants (activation energy, mainly) from some subcomponents of the processor and the trace of executed instructions. An alternative to such needs would be a pessimistic approach about the temperature, eliminating the need both of HotSpot and its inputs, and of RAMP. Chiaraviglio et al. [10] uses algebraic models of networks and many relations between variables and failure rates to ascertain that most probably using sleep modes on network devices increases the lifetime of devices. With a more straightforward analysis, we get a different result in Section IV.

## III. Failure Mechanisms

This work focuses on evaluating the processor's lifetime of the network devices. Due to space constraints, we detail here just the effects of thermal cycling, as this is the main point where our work diverges from the state-of-the-art. For a more complete description of other failure mechanisms, we refer the reader to [11] and [8]. For the purpose of this work, it suffices to know that failure mechanisms other than thermal cycling exist, and that they depend on the operating temperature. Additionally, their failure rates under temperature $T$ can be combined to obtain a single failure rate $\lambda_T$, which is related to the probability of a failure occurring at each infinitesimal instant of time. We now describe the failure mechanisms due to thermal cycling.

*1) Thermal cycling (TC):* The variation of the temperature may cause fatigue failures. The accumulation of these failures every time a thermal cycle happens eventually leads to failure [8]. Thermal cycling may be classified into two categories: large thermal cycles and small thermal cycles. The former type occurs at a low frequency (a few times a day). These are related to powering the processor up and down, or going into low power or stand-by modes. The second type occurs at a much higher frequency (a few times per second), being due to changes in workload or to context switching. Small thermal cycles have not been well studied by the community, what is to say that there are no validated models available [8]. The expected number of large thermal cycles are given by the Coffin-Manson equation [11]:

$$N_f = C_0(\Delta T)^{-q} \quad (1)$$

where $N_f$ is the average number of thermal cycles until failure, $C_0$ is a material-dependent constant, $\Delta T$ is the temperature range, and $q$ is a constant, the Coffin-Manson exponent [8]. For processors, the Coffin-Manson exponent $q$ is 2.35 [8]. In this work, we also call $N_f$ as Mean Cycles To Failure (MCTF), in order to make the statistical nature of this variable more evident.

Given a type of thermal cycle characterized by the temperature difference $\Delta T_1$ and the expected frequency of occurrence $f_1$, the MTTF implied by the MCTF is given by Equation 2:

$$MTTF_{TC} = \frac{MCTF_1}{f_1} = \frac{N_{f_1}}{f_1} \quad (2)$$

## IV. Exploring Thermal Cycling

With a network operation oriented to energy efficiency, it is expected that the equipment will be in different power states. This way, suppose that there are the power states $E_1, E_2$, and $E_3$, and that the thermal cycles can be of type 1, with amplitude $\Delta T_1$, occurring between $E_1$ and $E_2$, or of type 2, with amplitude $\Delta T_2$, occurring between $E_2$ and $E_3$. In these conditions, given that the processor was working before the first cycle, the probability of it be working after $x_1$ cycles of type 1 is $P_1 = e^{(-x_1/MCTF_1)}$. Analogously, if the processor is working properly before the first cycle of type 2, the probability of it be working after $x_2$ such cycles is $P_2 = e^{(-x_2/MCTF_2)}$.

Similarly, it can be proved that the reliability related to a period during which the processor undergoes $x_1$ cycles of type 1 and $x_2$ cycles of type 2, in no particular order, is given by Equation 3:

$$R = P_{1,2} = e^{-(\frac{x_1}{MCTF_1} + \frac{x_2}{MCTF_2})} \quad (3)$$

Equation 3 can be extended to include diverse types of cycles, that is, cycles of various amplitudes. Its predictive value is useful when there is an estimate about the occurring frequency of each type of cycle, as in the example below. This can be obtained from an estimate for the occurrence of power state transitions. Such occurrence depends on (i) the energy efficiency functionalities applied to the network, (ii) how these functionalities are managed, and (iii) the expected traffic profile of the devices.

### A. First Example

To give an example, we consider the operation of the Sustainability-oriented Network Management System (SustNMS) presented in [7]. Similarly, Gunaratne et al. [12] show statistics for the expected number of link rate transitions when using Adaptive Link Rate (ALR). Their result could be used in the same fashion as in the analysis of SustNMS. In the third experiment of [7], router R3 sleeps once and wakes up once. Likewise router R5 repeats this behavior three times. The topology is described in Figure 1. The experiment emulates 70 minutes of network operation. Therefore, suppose that during one day this sequence happens 16 consecutive times, followed by a period of idle operation during the night. In this situation the number of daily sleep-active cycles is 16 for R1 and 48 for R5. Suppose also that during the night both undergo 1 idle-active cycle. In addition, it is known that, in the absence of a network management system oriented to energy efficiency, the routers would not have gone into sleep mode, and would be idle during the nights. For this scenario, summarized in Table I, we want to analyze the impact of the energy efficient operation on the lifetime of the devices.

TABLE I. Daily thermal cycles, per router, per type of operation

| Cycles in 24 hours | Normal operation | | Sustainable operation | |
|---|---|---|---|---|
| | R3 | R5 | R3 | R5 |
| Sleep-active | 0 | 0 | 16 | 48 |
| Idle-active | 1 | 1 | 1 | 1 |

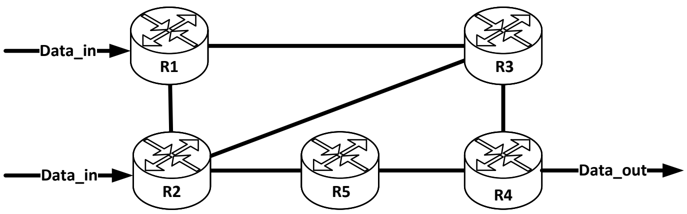


Fig. 1. Topology under the management of a network management system oriented to energy efficiency. Adapted from [7]

Being $s$ the sleep-active cycle and $o$ the idle-active cycle, we define $\Delta T_s$ as the average temperature variation in a $s$-cycle, and $\Delta T_o$ that in an $o$-cycle. Therefore, considering Equation 1, the average amounts of $s$- and $o-$cycles until failure are $MCTF_s = C_0(\Delta T_s)^{-q}$ and $MCTF_o = C_0(\Delta T_o)^{-q}$, where $C_0$ and $q$ are constants and identical in both types of cycle.

If, in the beginning of the 24-hour cycle under analysis, router R3 is operating correctly, then its reliability for one day (24h) of sustainable operation can be calculated by Equation 3:

$$R_{R3} = e^{-(16cycles/MCTF_s + 1cycle/MCTF_o)} = e^{-(16\lambda_s+\lambda_o)\times 24h},$$

where $\lambda_s$ and $\lambda_o$ are the failure rates occasioned by $s$-cycles and $o-cycles$, respectively. The sum $(16\lambda_s+\lambda_o)$ is the failure rate of the sustainable operation. The failure rate of the normal operation is $\lambda_o$. Therefore, for R3 the relationship $AF$ between the failure rates of the two types of operation, also known as acceleration factor, is:

$$AF_{R3} = (16\lambda_s + \lambda_o)/(\lambda_o) = 16 \times (\lambda_s/\lambda_o) + 1 = 16 \times [C_0(\Delta T_o)^{-q}/C0(\Delta Ts)^{-q}] + 1 = 16 \times (\Delta T_s/\Delta T_o)^q + 1.$$

Analogously, for R5 the acceleration factor is:

$$AF_{R5} = 48 \times (\Delta T_s/\Delta T_o) + q + 1.$$

Since $\Delta T_s$, $\Delta To > 0$, then $AF_{R3}, AF_{R5} > 0$ and thus the sustainable operation shortens the lifetime of both devices. This seems to contradict the recent predictions of Chiaraviglio et al. [10]. In the previous analysis, only failure mechanisms activated by thermal cycling were considered, since they are the most significant. Other failure mechanisms in processors and fans should be considered on the development of our ongoing work.

### B. Second Example

We now consider the effects of failure mechanisms other than thermal cycling (TC). The following discussion analyzes which constraints must hold in order for the penalty of cycling between power levels break even, from the point of view of reliability. Data from [10] and [9] will be used. Let $\lambda_{Told}$ be the combined failure rate due to failure mechanisms other than TC, in a not sustainable operation. Let $\lambda_{Tnew}$ be the correspondent rate, in a sustainable operation. It is advantageous to cycle to the sustainable operation if the reliability $R_{old}$ is less than or equal to $R_{new}$. By taking the transition cost into account, we get:

$$R_{new} \geq R_{old}$$
$$e^{-\lambda_{Tnew}\Delta T} \times e^{-\frac{1}{N_f}} \geq e^{-\lambda_{Told}\Delta T},$$

where $\Delta T$ is the time the device would stay in a sustainable operation and $N_f$ is the MCTF of the device. After a few algebraic manipulations on the exponents we get the following inequality:

$$1 \leq N_f(\lambda_{Told} - \lambda_{Tnew})\Delta T. \quad (4)$$

Now, from Figure 1 of [9] we get for $(\lambda_{Told} - \lambda_{Tnew})$ the value $0.0018315/year$ (considering a sustainable operation that gets 10% of savings). Chiaravilgio et al. [10] cite values of $N_f$ from 5000 to 10000. Inserting the values from [9] and the less restrictive $N_f$ of 10000 in Equation 4 yields:

$$1 \leq 0.05\Delta T, \quad (5)$$

with $\Delta T$ expressed in days. This means that, from the point of view of reliability, the duration of the sleep time should be greater than 20 days in order for the operation to break even. Such a situation is clearly in contradiction with the results of the dynamic scenario of [10], what means that more effort must be put to coalesce the different works in the area of reliability and power management.

## V. Discussion and Management Proposal

Previous work on the area of power management on systems-on-chip (SoCs) showed that thermal cycling is the most affected mechanism of failure [9]. With respect to failure mechanisms, in our ongoing work we have so far included solely thermal cycles. Such a decision is also present in [10].

Reduction of lifetime on sustainable networks brings new managerial concerns to network operators. As pointed out by Klingert et al. [13], "return on investment (ROI) is still the number one decision criterion when it comes to *evaluating green alternatives to current technology*". This way, the lifetime decrease of devices must be taken into account in order to achieve a more precise comparison between the costs of different network solutions (e.g., the use of different rates on links, or the adoption of sleep mode). A change in lifetime could result in significant change of the capital expenditure (CAPEX) of a solution .

To analyze the costs of different sustainable solutions we propose the use of dynamic programming. Dynamic programming is a technique to solve combinatorial optimization problems [14]. Some examples of such problems lie on the area of physical state transition systems and bioinformatics (especially when it comes to comparing DNA strings).

The statement of our dynamic programming problem is as follows. Let $E$ be a sequence of $e$ ordered traffic expectations, each $E_i$ denoting the expected traffic profile during a determined time duration $D_i$. Let the (operating) sequence $O_1, O_2, ..., O_e$ be a sequence of $e$ operating ways (methods). Let $T$ be an $e \times e$ table, with entry $T(i,j)$ holding the minimal cost of a green solution applied from $E_i$ to $E_j$. The function $G(e, d, o)$ is the cost (related to OPEX, the operational expenditure) of operating in an $o$ fashion throughout duration $d$ under expected traffic $e$. $T(i,j) = G(E_i, D_i, O_i)$, for $i = j$. In any other case, there exist $j - i$ possible splittings of the operating sequence into two parts $(O_i, ..., O_k)$ and $(O_{k+1}, ..., O_j)$. The total cost of such an (split) operating sequence is the cost associated to the first part, plus the cost $C(k, k+1)$ associated to the transition from $O_k$ to $O_{k+1}$, plus the cost associated to the second part. This way, the best operating sequence can be optimal only if the partial sequences are optimally operated. We can therefore populate the matrix T in a triangular fashion, as described in Algorithm 1.

**Algorithm 1:** Cost optimization algorithm

```
for j = 1 to e do
   for i = j to n do
      A_ikj = T(i,k) + C(k,k+1) + T(k+1,j)
      B_ikj = T(i,k) + sum_{l=k+1}^{j} G(E_l, D_l, O_k)
      T(i,j) = min{A_k, B_k | i <= k < j}
return T(1,e)
```

$$A_{ikj} = T(i,k) + C(k,k+1) + T(k+1,j)$$
$$B_{ikj} = T(i,k) + \sum_{l=k+1}^{j} G(E_l, D_l, O_k)$$
$$T(i,j) = min\{A_k, B_k | i \le k < j\}$$

Populating the matrix as described above gives the optimal cost for $T(i,j)$, and thus to the whole operation throughout the time during which the expected traffic holds. Not just it gives the optimal cost, but it also calculates which modes should be applied in order for the cost to be optimal. Therefore, the solution of the presented dynamic programming problem also corresponds to policies to be applied to the network.

## VI. Conclusions

We showed that a sustainable network operation most likely leads to reduction of equipment lifetime, mainly due to thermal cycling. This result is in contradiction with a previous prediction [10] but is in agreement with the overwhelming effects of thermal cycling pointed out in [9]. We are now working on a cost analysis tool based on dynamic programming able to punctuate the trade-offs among energy efficiency, performance, availability, and lifetime reliability, thus yielding an operation policy based on expected traffic profile. Works like [8] and [9] focus on a single device, whereas in the context of networks we must look at the environment as a whole. To conclude, we believe that the losses (economically speaking) caused by sustainable functionalities will be surpassed by the gains caused by energy savings, thus making sustainable operations even more feasible. Our network management tool would be a guide in analyzing such intricate scenario.

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