To Sleep or Not to Sleep: Understanding the Social Behavior of Lifetime-Aware Networks

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Abstract. Network lifetime is one of the key characteristics for evaluating wireless sensor networks (WSNs) in an application-specific way based on the availability of sensor nodes, wireless radio coverage, and wireless connectivity. Basically it shows in a resource constrained environment the consumption of every limited resource must be considered. A large number of energy efficient protocols and algorithms have been proposed in WSNs, mainly by introducing a sleep mode (SM) state to prolong the lifetime of a sensor network. The network nodes or links can be switched between working and sleep modes dynamically according to the real-time traffic situations. While there are far less critical discussions on what can be the negative effects of SMs on network lifetime in terms of hardware reliability such as failure rate. The duration of SMs tends to increase hardware lifetime, while the frequency of power state transitions tends to decrease it. In this paper, we extend the lifetime concepts in WSNs to wired network to reveal the side-effects of SMs on the hardware reliability. We have extensively studied the lifetime behavior of network links in a backbone network scenario as well as identified the sensitive social factors impacting the network lifetime. This novel research dimension is thought-provoking and opening a new conversation for researchers who are working in the areas of sustainable communications and computing to rethink and redesign the energy efficient approaches so as to address their possible side-effects on hardware reliability for the next stage of their implementation.

Keywords: Lifetime-aware networking · Energy efficiency · Reliability · Failure rate and analysis · Social behavior

1 Introduction

Lifetime-aware network is one of most important research topics in sensor networks which are under the resource-constrained environments and the consumption of every limited resource must be considered. It is a key characteristic for

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evaluating wireless sensor networks (WSNs) in an application-specific way based on the availability of sensor nodes, the wireless radio coverage, and the wireless connectivity. Even the quality of service (QoS) measures can be related to lifetime considerations[1]. The network lifetime can be a measure of energy consumption occupies the exceptional position since it decides the upper time bound for the utility of a sensor network. The network can only fulfill its communications purpose as long as it is considered alive but not after that. It is therefore an indicator for the maximum utility and service of which a sensor network can provide. Lifetime studies first came up because the recharging or replacement of batteries is not feasible in many scenarios e.g., too many nodes, hostile environment etc., and thus the lifetime of network cannot be extended infinitely. If network lifetime metric is used in an analysis on a real life deployment, the estimated network lifetime can also contribute to moderate the cost of the deployment. Lifetime is also considered as a fundamental but very critical parameter in the context of availability and security in networks[2]. Network lifetime strongly depends on the lifetimes of single nodes or links that constitute the network. This fact does not depend on how the network lifetime is defined. Each definition can finally be interpreted to the fundamental question of when the individual node or link fails. Thus, if the lifetime of single node or link are not predicted accurately, it is possible that the derived network lifetime metric will deviate in an uncontrollable manner. It should therefore be clear that accurate and consistent modeling of single node or link is very important. The lifetime of a sensor node basically depends on two factors according to the literature[3]: how much energy it consumes over time, and how much energy is available for its use.

In the literature, we can find a great number of relevant publications that address the problem of sensor network lifetime and how to prolong it by introducing a sleep mode (SM) state and exploiting the possibility to enable the sensor node with SMs as much as possible to save energy consumption. When a SM state is set for a device in a network, the other nodes that remain powered on have to sustain the traffic flows between the source and destination nodes. This promising SMs approach has been applied into the wired networks and different works have investigated the management of backbone networks by adopting sleep modes (SMs)[4–7]. The main outcome of these works is that networks with SM enabled are able to save a significant amount of energy, due to the fact that the traffic experiences high fluctuations between the day and the night, resulting in a large number of resources that can be put in SMs during off peak hours. However, the impact of SMs on the reliability of network devices is an open issue[8,9]. In particular, there are two opposite effects influencing the lifetime of network devices[10]: the duration of SMs tends to increase the lifetime, but the change frequency of the power state (i.e., from SM to full power and vice versa) has the opposite effect, i.e., lifetime decrease. When a device experiences a failure, the device may not be available any more to accommodate traffic forwarding, resulting in a Quality of Service (QoS) degradation for users. Additionally, the reparation costs are incurred, which may involve even the replacement of the whole device. In particular, the reparation costs may even exceed the monetary savings gained from SMs[11]. These all facts suggest that the lifetime of the devices plays a crucial role in determining the effectiveness of SMs, showing that the energy saving may be not the only metric to prove the effectiveness of a SM-based approach.

The remainder of the paper is organized as follows. The mathematical model adopted for evaluating the network lifetime is presented in Sec. 2. Sec. 3 defines and formulates the lifetime aware network problems. A backbone network scenario is introduced for setting up the numerical studies in Sec. 4, and Sec. 5 has conducted the simulation studies and then the results analysis is presented to explain the different network lifetime behavior of each network resource. Discussion of our work is reported in Sec. 6. The final conclusion is drawn and future work is laid out in Sec. 7.

2 The Network Lifetime Model

We first review the model of [9,10] to compute the network lifetime. Here we report the main intuitions, while we refer the reader to [10] for the complete models. In particular, our focus is on links of a backbone network. The generic failure rate for a link at full power is defined as γ^{on}. The failure rate is the inverse of the lifetime. When SM is applied into the link, the new failure rate γ^{tot} is defined as:

$$\gamma^{tot} = \underbrace{\gamma^{on}\left(1 - \frac{\tau^{off}}{T}\right) + \gamma^{off}\frac{\tau^{off}}{T}}_{\text{Failure Rate Decrease}} + \underbrace{\frac{f^{tr}}{N^F}}_{\text{Failure Rate Increase}} \tag{1}$$

where τ^{off} is the total time in SM during time period T, γ^{off} is the failure rate in SM, f^{tr} is the power switching rate between full power and SM, and N^F is a parameter called number of cycles to failures. Thus, the total failure rate is composed by two terms: the first one tends to decrease the failure rate, while the second one has the opposite effect.

In order to evaluate the lifetime increase or decrease w.r.t. the always on solution, we define a metric called Acceleration Factor (AF). The AF is lower than one if the link lifetime is increased compared to the always on solution. On the contrary, a value higher than one means that the lifetime is decreased compared to the always on case. More formally,

$$AF = \frac{\gamma^{tot}}{\gamma^{on}} = 1 - \underbrace{(1 - AF^{off})\frac{\tau^{s}}{T}}_{\text{Lifetime Increase}} + \underbrace{\chi f^{tr}}_{\text{Lifetime Decrease}} \tag{2}$$

where AF^{off} is defined as $\frac{\gamma^{off}}{\gamma^{on}}$, which is always lower than one since the failure rate in SM γ^{off} (by neglecting the negative effect due to power state transitions) is always lower than the failure at full power γ^{on}. Moreover, χ is defined as $\frac{1}{\gamma^{on} N^F}$, which acts as a weight for the power frequency rate f^{tr}. The AF is then composed of two terms: the first one which tends to increase the lifetime (longer periods of SMs tends to increase this term which is negative), instead the second one tends to decrease the lifetime (the more often power state transitions occur, the higher this term will be). Moreover, the model is composed by parameters AF^s and χ, which depend solely on the hardware components used to build the device, while parameters τ^s and f^{tr} depend instead on the specific SM strategy. In the following, we detail the optimization model for minimizing the AF of a set of links.

3 Problem Definition

We consider an Internet Service Provider (ISP) network, where nodes are sources and destinations of aggregated traffic requests generated by users. We also assume that the links capacity and the traffic demand by all source/destination node pairs for each time period are given. Our objective is to find the set of links that must be powered on so that the total AF in the network is minimized, subject to flow conservation and maximum link utilization constraints. More formally, we report the formulation of the problem of [12]. More in depth, let $G = (V, E)$ be the graph representing the network infrastructure. Let V be the set of the network nodes, while E the set of the network links. We assume $\mid V \mid= N$ and $\mid E \mid= L$. Let $c_{i,j} > 0$ be the capacity of the link (i, j) and $\alpha \in (0, 1]$ the maximum link utilization that can be tolerated in order to avoid congestion and to guarantee over-provisioning. Let us denote as T the total amount of time under consideration. T is divided in time slots of period δ_t. Finally let $t^{s,d}(k) \geq 0$ be the traffic demand from node s to node d during slot k.

Focusing on the variables, we denote with $f_{i,j}^{s,d}(k) \geq 0$ the amount of flow from s to d that is routed through link (i, j) during slot k. Similarly, we denote as $f_{i,j}(k) \geq 0$ the total amount of flow on link (i, j) during slot k. Moreover, let $\tau_{i,j}^{off} \geq 0$ be the total time in sleep mode of link (i, j). Finally, let us denote with $AF_{i,j} \geq 0$ the AF for link (i, j).

In the following, we consider the integer variables. Let us denote with $x_{i,j}(k)$ a binary variable which takes value one if the link (i, j) is powered on during slot k, zero otherwise. Moreover, let us denote with $\xi_{i,j}(k)$ a binary variable which takes value one if link (i, j) has experienced a power state transitions from slot $k - 1$ to slot k, zero otherwise. Additionally, $C_{i,j} \geq 0$ are integer variables counting the number of power state transitions for link (i, j).

Given the previous notation, the objective is to minimize the total AF in the network:

$$\min \frac{1}{L} \sum_{(i,j) \in E} AF_{(i,j)} \tag{3}$$

We then consider the constraints. In particular, traffic has to be routed in the network:

$$\sum_{j:(i,j)\in E} f_{i,j}^{s,d}(k) - \sum_{j:(j,i)\in E} f_{j,i}^{s,d}(k) = \begin{cases} t^{sd}(k) \text{ if } & i = s \\ -t^{sd}(k) \text{ if } & i = d \\ 0 \text{ if } & i \neq s, d \end{cases} \quad \forall i \in V \quad \forall k \tag{4}$$

We then compute the total amount of traffic on each link:

$$f_{i,j}(k) = \sum_{s,d} f_{i,j}^{s,d}(k) \quad \forall (i,j) \in E \quad \forall k \tag{5}$$

And we impose the maximum link capacity constraint:

$$f_{i,j}(k) \leq \alpha c_{i,j} x_{i,j}(k) \quad \forall (i,j) \in E \quad \forall k \tag{6}$$

Additionally, links have to assume the same power state in both directions:

$$x_{i,j}(k) = x_{j,i}(k) \quad \forall (i,j) \in E \quad \forall k \tag{7}$$

We then count the number of power state transitions for each link:

$$\begin{cases} x_{i,j}(k) - x_{i,j}(k-1) \leq \xi_{i,j}(k) \\ x_{i,j}(k-1) - x_{i,j}(k) \leq \xi_{i,j}(k) \end{cases} \quad \forall (i,j) \in E \quad \forall k \tag{8}$$

Moreover, we count the total number of transitions for each link:

$$C_{i,j} = \sum_k \xi_{i,j}(k) \quad \forall (i,j) \in E \tag{9}$$

And also the total time in SM for each link:

$$\tau_{i,j}^{off} = \sum_k (1 - x_{i,j}(k)) * \delta_t \quad \forall (i,j) \in E \tag{10}$$

Finally, we compute the total AF for each link:

$$AF_{i,j} = [1 - (1 - AF_{(i,j)}^s) \frac{\tau_{i,j}^{off}}{T} + \chi_{(i,j)} \frac{C_{i,j}}{2}] \quad \forall (i,j) \in E \tag{11}$$

The total number of transitions is divided by two since we assume that a power cycle is always composed of two transitions.

4 Scenario Description

We adopt the Orange - France Telecom (FT) scenario of [13]. Tab. 1 reports the main network characteristics. We refer the reader to [13] for more details. Here we report a brief summary. In brief, the FT network comprises the core level of the network. The topology, reported in Fig. 1, is composed of 38 nodes and 72 bidirectional links. Additionally, link capacities and routing weights are provided.

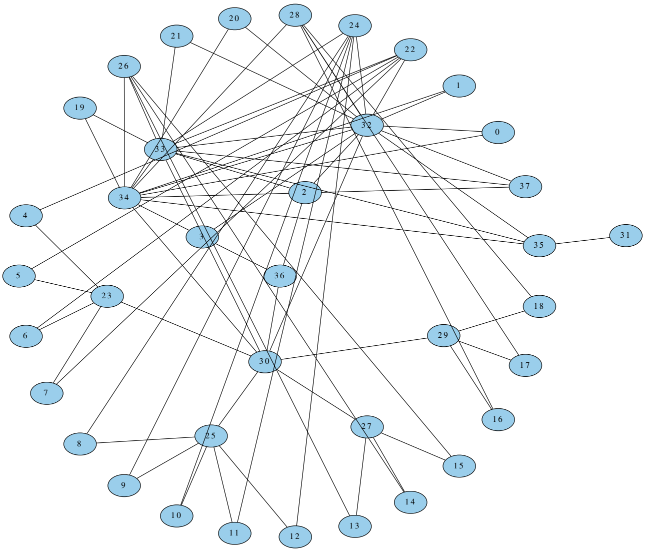

Fig. 1. Orange-FT network topology

More in depth, the FT network provides specific weights used to balance the load in the network. Finally, focusing on power consumption, we have adopted the same power model of [14], in which each link consumes an amount of power corresponding to a pair of transponders and a pair of IP interface ports. Each 10 Gbps transponder consumes 37W and each 1 Gbps port consumes 10W. Finally, we assume that when a link is in sleep mode, the power consumption is negligible.

Together with the topology, we have considered different sets of traffic matrices provided by the operator, together with the source and destination nodes. A total of 289 matrices is provided, which covers a working day. The total traffic (normalized to one) over time is reported in Fig. 2. As expected, traffic exhibits a strong day-night trend, with a peak during the day and an off peak during the night.

Finally, the maximum link utilization α is set to 50%, as recommended by the operator.

5 Case Studies

Since the presented problem is very hard to be solved due to the high number of links in the FT topology, as well as the number of TMs, we have followed a heuristic approach. In particular, we have applied the Most Power (MP) heuristic [6] for each TM, and we have then computed as a post-processing phase the resulting AF. The main idea of the MP heuristic is to put in SM the largest number of links, by ordering them in descending value of power to selectively

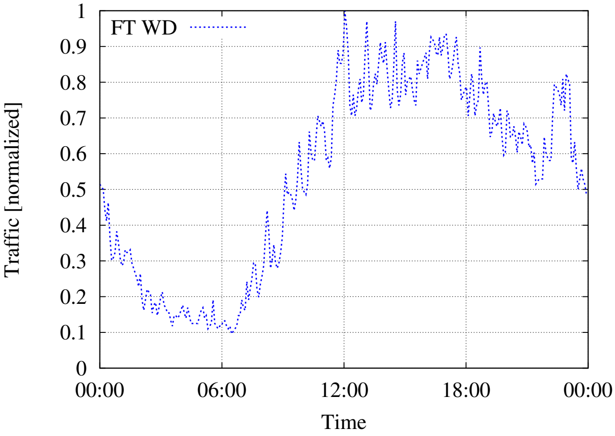

Fig. 2. Traffic profile for the Orange-FT scenario

Table 1. Network Characteristics

Parameter	FT
Type	Core Level
Number of Nodes	38
Number of Links	72
Average Degree	3.78
Routing Weights	Provided by Operator
Routing Algorithm	Min. Cost Path
Traffic Variation	1 working day

put them in SM. For each link put in SM, the connectivity and maximum link utilization constraints are verified. If they are not met, the link is put at full power, otherwise it is left in SM.

In our scenario, we have considered a time period of 15 days, and the repetition of the same traffic profile over the days. Moreover, we have set the hardware parameters as $\chi_{(i,j)} = 0.5$ and $AF^{off} = 0.2$ for all the links. In this way, the gain in terms of lifetime from putting in SM links is high, but we consider also a penalty $\chi_{(i,j)}$ not negligible for the transitions.

The Fig. 3 reports the values of the AF for each link in the network at the end of the 15 days period. Interestingly, we can see that the observed AF is not the same for all the links, with some links having an AF close to one and others instead with larger AF (i.e. more than four). This suggests that the lifetime behavior is not the same for all components in the network, with some links that decrease the lifetime and others instead which tends to keep it similar compared to the full power solution. Thus, we can clearly see that the lifetime depends on the particular device in the topology. In particular, it is a metric that depends on the global conditions of the network (i.e. guaranteeing connectivity

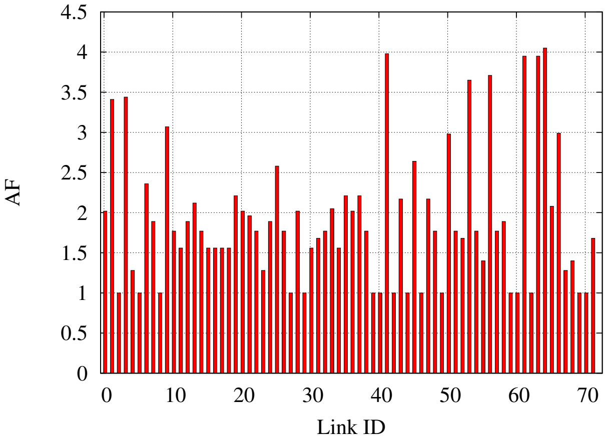

Fig. 3. AF for each link in the topology

and maximum link utilization), but also on the local policy adopted to decide when to put in SM the network device.

To give more insight, the Fig. 4 reports the network topology with the link width proportional to the measured AF. Interestingly, the links with the largest value of AF (i.e., consequently lower lifetime) are the ones that are connected to at least one node with high degree (e.g., 30,32,33,34). In particular, these links are frequently put in SMs to save energy and then powered on to support the traffic flows. Thus, the resulting lifetime is significantly decreased due to the fact that there are a lot of power state transitions occurred. This suggests that also the position of the link in the network topology strongly influences its AF too. In other words, the ways of links being connected play a crucial role for its lifetime.

In the following, we consider the evolution of AF over the time. Fig. 5 reports the AF vs. time for four different links in the topology. Interestingly, also the AF tends to vary notable vs. time. In particular, links 4-23, 19-33 and 20-32 experience an AF less than one in the first two days, meaning that at the beginning their lifetime tends to be increased compared to full power solution. However, in the following days, their AF is higher than one, meaning that the lifetime is reduced. This suggests also that time needs to be considered as one of sensitive factors for the lifetime.

In the last part of our work, we have considered the variation of the hardware parameters χ and AF^{off}. Fig. 6 reports the variation of the average AF in the network vs. the hardware parameters. In particular, when AF^{off} is increased, the AF is increased too: this is due to the fact that the gain for putting in SM devices is smaller compared to low values of AF^{off}. Additionally, the lifetime tends to be decreased when the penalty for power state transitions is increased. This suggests also that the lifetime management should take into account the hardware parameters, which depends on how the single devices are being built.

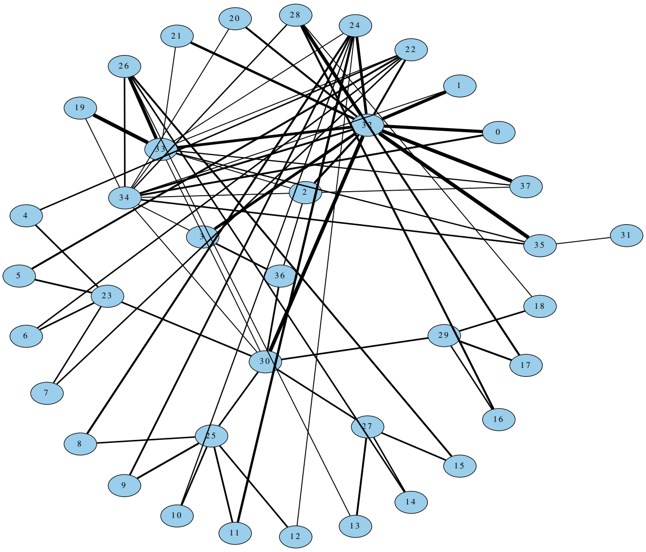

Fig. 4. FT/Orange Topology. The link width is proportional to the AF value.

6 Discussion

The presented results pointed out some interesting insights about the social behavior of lifetime-aware networks. First of all, the lifetime is not the same for all devices in the network, with some devices increasing the lifetime and other keeping it almost constant. This is due to the following factors: i) the specific algorithm used to select the links in sleep mode, ii) the traffic variation over time,

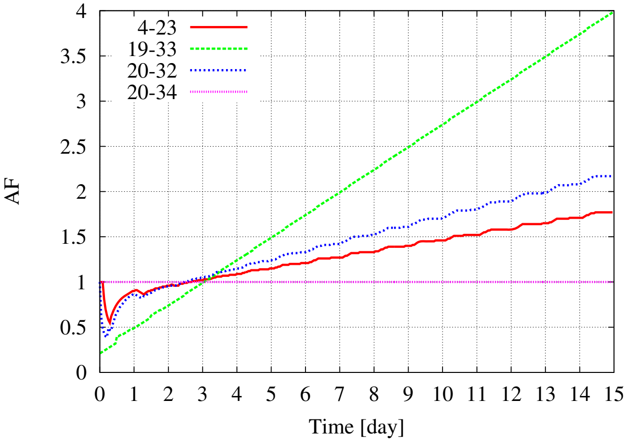

Fig. 5. AF vs. time for a set of links in the topology

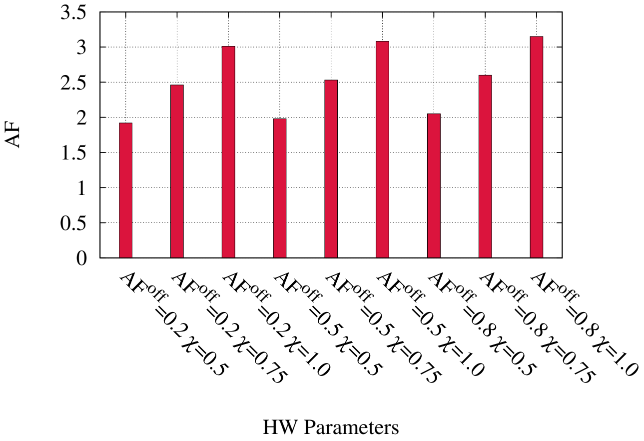

Fig. 6. AF values vs. the variation of HW parameters χ and AF^{off}

iii) the network topology under consideration, and iv) the HW parameters. Thus, we may claim that there exists a social behavior in this scenario: each link has to optimize its own lifetime, but this metric depends on both endogenous (e.g. the HW parameters) and exogenous parameters (e.g. the power state of the other links in the network). Additionally, also the link position in the topology tends to influence the lifetime, i.e., the links connected to the nodes with the highest degree (i.e. the highest number of "connections") tend to vary more notably their lifetime. Moreover, we have seen that the lifetime changes over time, passing from the situation in which it is clearly increased (e.g. during the initial days) to the case in which it is decreased (e.g. during the last days under consideration). Clearly, also this issue should be considered as future direction of investigation for our work.

7 Conclusions and Future Work

We have studied the impact of applying a sleep mode based algorithm on a telecom backbone network, with an emphasis on its social behavior. We have first proposed a simple model to evaluate the lifetime increase or decrease of network links as a consequence of sleep mode. After optimally formulating the problem of maximizing the lifetime of a set of links in a backbone network, we have conducted an extensive case study to validate the lifetime behavior of network links. Our results show that the link lifetime is influenced by the position of the link in the topology, as well as endogenous (e.g. the HW components used to build the link) and exogenous parameters (e.g. the current set of links in SM, and the traffic in the network). Moreover, we have shown that the lifetime varies over time. As next step, we plan to develop an algorithm that is able to consider the aforementioned social effects, as well to study the impact of traffic matrix on the lifetime.

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