Energy-Efficiency Analysis Under QoS Constraints Using Formal Methods: A Study on EPONs

Sophia Petridou
Department of Applied Informatics
University of Macedonia
Thessaloniki, Greece
Email: spetrido@uom.edu.gr

Stylianos Basagiannis
United Technologies Research Centre
Cork, Ireland
Email: basagis@utrc.utc.com

Lefteris Mamatas
Department of Applied Informatics
University of Macedonia
Thessaloniki, Greece
Email: emamatas@uom.edu.gr

***Abstract*—In Ethernet Passive Optical Networks (EPONs), the equipment placed at the customer premises, i.e., the Optical Network Units (ONUs), has been shown to be responsible for almost 65% of the total EPON power consumption. Sleep mechanisms, implemented at ONUs' side, can contribute to the EPONs energy efficiency. However, the trade-off between energy saving and Quality of Service (QoS) requirements should be carefully tuned, especially when the downstream transmission is considered, in order to achieve the desirable results. In this paper, we exploit formal methods in order to build a holistic model representing both the state machine of the ONU in its details as well as the ONU's communication with the Optical Line Terminal (OLT) under EPONs specifications. The quantitative results of our analysis highlight the impact of the non-active periods on the aforementioned trade-off and shows how they can be configured in line with the network parameters.**

I. Introduction

Nowadays, energy efficiency in Ethernet Passive Optical Networks (EPONs) attracts a lot of attention due to a challenging phenomenon: optical access networks consume less energy per transmitted bit compared to the current xDSL-based wired access, but, it is estimated that they will be the largest energy consumers among the wired access networks for the next ten years [1]. At the same time, within EPONs, the Optical Network Units (ONUs) are the most energy-consuming devices, since they are responsible for almost 65% of the total EPON power consumption [1].

Therefore, a common approach to improve EPONs energy efficiency is to turn off (completely or partially) the ONUs, which are rarely used at their full potential, in a cyclic manner, known as fast sleep [2]–[5]. Two challenging tasks of a sleep mechanism are to determine the conditions that trigger the sleep state, as well as the sleep state duration [6].

In this paper, we propose a formal analysis approach to study energy efficiency in EPONs. Our goal is to build a holistic model which represents the ONU state machine in its details and simultaneously synchronizes it with the specifications of an EPON. Towards this goal, formal techniques, such as probabilistic model checking, are the perfect candidate, since they can be applied to analyse systems that exhibit stochastic behaviour, e.g., communication protocols and computer networks [7]–[9].

To the best of our knowledge this is the first time that a passive optical network is analysed using formal methods. The EPON under consideration is modeled as a Continuous-Time Markov Chain (CTMC), $\mathcal{EPON}_{\mathcal{CT}}$ model, while its properties are expressed as Continuous Stochastic Logic (CSL) formulas [10]. CTMCs, frequently used in performance analysis, model continuous real time and probabilistic choice: one can specify the rate of making a transition from one state to another [7].

For the sake of the proposed analysis, the initial step was to model the ONU finite state machine. Apart from the three power states considered, namely the active, listen and sleep, the $\mathcal{EPON}_{\mathcal{CT}}$ model elaborates on transitions rates, derived by the recent bibliography [3], [4], [11], and especially on the wake-up delay which, according to [4], [6], should be taken into account by a sleep mechanism. The precision in transitions' rates highlights the impact of the listen and sleep periods' duration. Intuitively, short sleep periods are preferable when QoS requirements are stringent, e.g., schedule of delay-sensitive traffic, but they can be prolonged, guided by the QoS constraints, keeping the energy saving as the primary goal. Our analysis provides quantitative results verifying this intuition.

The challenge afterwards was to align the model to the EPONs' specifications. For this purpose, a number of network parameters are considered, e.g., the rate of the downlink channel, the packets' length, arrival and service rate. In addition, a queue is modeled at the Optical Line Terminal (OLT) to buffer the packets arriving while the ONU is sleeping. Finally, the $\mathcal{EPON}_{\mathcal{CT}}$ model is augmented with rewards (or costs) expressing power consumption at each ONU state. This way, energy-related results can be derived.

The novelty of the proposed work is summarized as follows:

- it exploits formal methods and especially model checking as a means of tuning the trade-off between energy saving and QoS requirements, e.g., packets' delay, in an EPON,
- it combines the state machine of the ONU with the EPONs' specifications in order to build a configurable CTMC model,
- it demonstrates the impact of the listen and sleep periods on the aforementioned trade-off and specifies their duration in an EPON case study.

The remainder of this paper is organized as follows. Section II provides a brief review of related studies. Section III explains formal verification preliminaries, while Section IV describes the proposed $\mathcal{EPON}_{\mathcal{CT}}$ model. The results of the analysis are discussed in Section V. Finally, Section VI concludes the paper.

II. Related Work

SIEPON (Service Interoperability in Ethernet Passive Optical Networks) standard [12] describes mechanisms and protocols for reducing the ONU power consumption based on power saving states. But, the parameters that determine the conditions that trigger the sleep state and the sleep state duration are outside the scope of the standard, leaving room for further investigation. In the literature, there have been approaches focused on the physical or data link layer and some of them target both layers via hybrid solutions [2]. The schemes that operate on the data link layer are either OLT or ONU-triggered based on a control message flow [3], [13], [14] or self-triggered based on mutual OLT and ONU consent [5], [15].

Energy-saving solutions of the latter case have the advantage of minimum or no overhead, since they address the downstream challenge through the modification of the bandwidth allocation (BA) algorithms running at both sides of communication. Lee *et al.* [16] propose fixed bandwidth allocation (FBA) for the downstream traffic under light network load. Using FBA, the ONUs are allocated with fixed and a priori known time slots. Thus, they can transit to the sleep state during the time slots assigned to the rest ONUs, without any OLT notification. However, FBA suffers from bandwidth under- or over-allocations. Yan *et al.* [17] provide the solution of simultaneously scheduling the downstream and upstream traffic, since the receivers and transmitters operate at different wavelengths. The idea is that an ONU can receive its downstream traffic over the time slots that its upstream traffic is scheduled and they are assigned to it by the OLT. While this scheme works efficiently under symmetric traffic, it deteriorates bandwidth utilization when downstream traffic outweighs upstream traffic (e.g., downloading, broadcast TV).

In [5], [15], Zhang *et al.* achieve high bandwidth utilization by exploiting dynamic bandwidth allocation (DBA). They use a semi-Markov chain and consider three possible states for the ONU's operation, namely the active, listen and sleep state. In their solution, the ONU's receiver transits from the active to the listen and, then, from the listen to the sleep state based on the downstream traffic scheduling performed by the OLT. In particular, if the ONU does not receive downstream traffic for a time period x, it transits to the sleep state for a time period y. The ONU can interrupt the listen period x because of incoming downstream traffic, but once it transits to the sleep state, it should wait for the sleep period y to be expired.

A major issue is that this solution handles the listen and sleep periods, represented as x and y, in quite a conservative way. In particular, they prioritize QoS constraints, e.g., packets' delay, independent of the traffic identity, e.g., delay-insensitive traffic. But, the trade-off between QoS requirements and desirable energy conservation results into shrinking energy saving even when this is not required. Another issue is that

TABLE I
BASIC SYMBOLS' NOTATION

Parameter	Notion
C	rate of the downlink channel (1.25 $Gbps$)
$packets$	number of transmitted packets
L	packets length (1 518 $bytes$)
λ	packet arrival rate
μ	packet service rate (C/L)
R_{l2s}	rate of listen to sleep transition ($1\,000/2.88$)
R_{s2l}	rate of sleep to listen transition ($1/2$)
R_{s2a}	rate of sleep to active transition ($1/2$)
d_{listen}	listen period duration ($d_{listen} = 1/R_{l2l}$)
d_{sleep}	sleep period duration ($d_{sleep} = 1/R_{s2s}$)

the analysis of Zhang *et al.* [5], [15] does not consider the recovery overhead. Typically, the ONU's transition from the sleep to the active state (wake-up) is not instantaneous, but it requires quite a long time ($\sim 2ms$). This overhead is twofold: the ONU must recover the OLT clock and regain the network synchronization [4]. This parameter affects the state machine of the ONU as well as the delay-related results.

III. Formal Verification for EPONs' Energy Analysis

Formal verification is a popular approach towards the validation and verification of computer-based systems [18], [19]. Its power is based upon a fully automated technique of verifying that the system under consideration - an EPON in our case - will meet its requirements, e.g. in terms of QoS or energy-efficiency. Typically, a system model M is required and then probabilistic model checking, which is a quantitative formal verification technique, proceeds to a systematic inspection of all generated states of M to verify its desirable reachability properties [19]. This way, an EPON sleep mechanism can be quantitatively verified through automatically checking the reachable states of its corresponding model M, designed in line with energy-aware and network specifications.

An EPON is a real-time system mastered by packets' exchange between an OLT and ONU(s) over an fibre-optic line. A sleep mechanism implemented at the ONUs' side implies a certain discrete-step functionality for the devices into communication. Thus, from a model checking perspective, CTMC is a suitable choice, since it forms a set of labelled transition states augmented with rates, used to derive quantitative results tuning the trade-off between energy saving and QoS requirements, i.e., packets' delay.

A. Probability Analysis

Probability analysis allows us to derive quantitative results computing the probability that some behaviour of a model is observed, e.g., the probability that the ONU will be in sleep state for a given duration of listen period. The proposed $\mathcal{EPON}_{\mathcal{CT}}$ Markov chain model is defined as a tuple $(S, \bar{s}, R, L)$, where:

- S is a finite set of states
- $\bar{s} \in S$ is the initial state
- $R : S \times S \to \Re_{\geq 0}$ is the transition rate matrix and

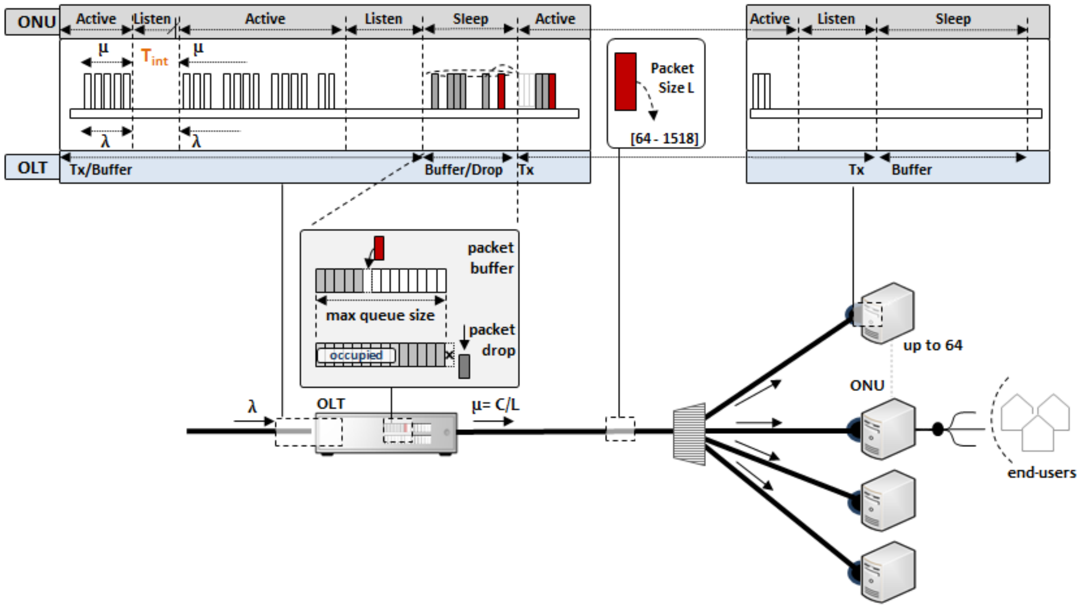

Fig. 1. The components of the $\mathcal{EPON}_{\mathcal{CT}}$ Markov chain model

- $L : S \rightarrow 2^{AP}$ is the labelling function of atomic propositions AP that are true in S.

Our model specifies the transition rate matrix R, which provides the rate of making a transition from state s to s' within time t. For this transition, the actual probability will be $1 - e^{-R(s,s')\cdot t}$. Thus, the transition probability $P(s, s')$ in a single step will be:

$$P(s,s') = \begin{cases} \frac{R(s,s')}{\sum_{s'' \in S} R(s,s'')} & \textit{if } s'' \neq s' \\ 1 & \textit{if } s = s' \\ 0 & \textit{if } s \neq s' \end{cases}$$

Matrix R is calculated in line with the rates $\lambda, \mu, R_{l2l}, R_{l2s}, R_{s2s}, R_{s2l}, R_{s2a}$ defined in Table I and discussed in Section IV.

B. QoS and Energy-Aware Properties

For the sake of the energy-efficiency analysis it is essential to receive not only probabilistic results, but also quantitative measures related to model's behaviour, e.g., the expected energy saving. Thus, once the $\mathcal{EPON}_{\mathcal{CT}}$ model is designed, it is augmented with reward structures, which embeds power consumption cost in Watt (W). More specifically, an ONU receiver is considered to consume $3.85W$, $1.28W$ and $0.75W$ in the active, listen and sleep state, respectively [4].

For $\mathcal{EPON}_{\mathcal{CT}}(S, \bar{s}, R, L)$, a reward structure is a tuple (ϱ, ι), where:

- $\varrho : S \rightarrow \Re_{\geq 0}$ is a vector of state rewards, and
- $\iota : S \times S \rightarrow \Re_{\geq 0}$ is a matrix of transition rewards.

Among four different types of reward properties supported in CTMC models [7], we employ:

- *Instantaneous* $R_{\bowtie r}[\mathrm{I}^{=t}]$: the expected value of the reward at time-instant t is $\bowtie r$, and
- *Cumulative* $R_{\bowtie r}[\mathrm{C}^{\leq t}]$: the expected reward cumulated up to time-instant t is $\bowtie r$,

where $\bowtie \in [\leq, <, \geq, >]$. In our analysis, instantaneous rewards provide the expected packets' delay, while cumulative rewards calculate the expected power consumption. Time property for these rewards is typically derived through probabilistic results.

IV. EPON Modeling using CTMC

From the model checking perspective, the ONU state machine and its optical communication with the OLT are modelled as a CTMC within the PRISM model checker [20]. Our $\mathcal{EPON}_{\mathcal{CT}}$ model, comprises three (3) modules, namely $M = \{M_{olt}, M_q, M_{onu}\}$. In line with the Fig. 1:

- M_{olt} corresponds to the OLT, which broadcasts a number of $packets$ and observes the ONU state,
- M_q represents a queue for modeling the packets' arrival, their buffering once they cannot be immediately received by the ONU and their dropping when the queue is full,
- M_{onu} models the ONU, which receives the packets that have been transmitted. This component may typically have several states of operation, each of which is characterized by a service rate. In general, states with zero service rate are called sleep states.

Each module M_i, $i = \{olt, q, onu\}$, is defined as a pair of (Var_i, C_i), where Var_i is a set of integer-valued local variables and C_i is a set of commands which drive the behaviour of the module. Each command $c \in C_i$ is written as $[\ ]g \rightarrow \lambda_1 : u_1 + \ldots + \lambda_n : u_n$, composing of: a synchronization label $[\ ]$, a guard g and a set of pairs (λ_j, u_j), $1 \leq j \leq n$. The guard g is a predicate over the set of all local variables Var and each update u_j corresponds to a possible transition of module M_i. The constants λ_j

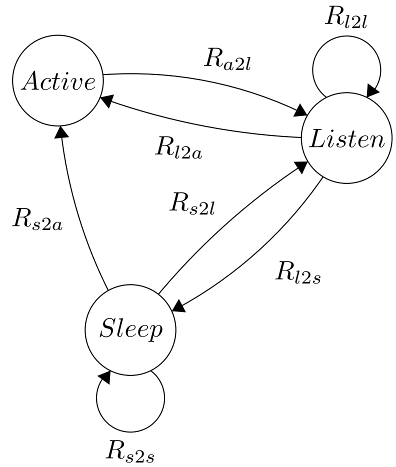

Fig. 2. The ONU finite state machine

determine the rates attached to the transitions [18]. In our case $\lambda_j \in \{\lambda, \mu, R_{l2l}, R_{l2s}, R_{s2s}, R_{s2l}, R_{s2a}\}$.

The $\mathcal{EPON}_{\mathcal{CT}}$ model considers three possible ONU states, namely active, listen and sleep state, inspired by the scheme proposed in [5], [15]. However, contrary to [5], [15], where the transit time from the sleep and the active state is considered to be negligible and, thus, is not taken into account, the proposed analysis elaborates on transition times which are derived by the recent studies [3], [4], [11]. This way we can appropriately configure the parameters that specify the listen and sleep periods, which significantly affects the trade-off between energy saving and packets' delay.

In brief, at any given time, the ONU can only be in one of the aforementioned three states, shown in Fig. 2. As depicted in Fig. 1, the ONU receives downstream packets only in the active state with service rate μ. Once the ONU does not receive data during a scheduling cycle, it transits to the listen state for a period of d_{listen} duration. The time d_{listen} specifies the rate to stay in the listen state, i.e., $R_{l2l} = 1/d_{listen}$. The transit time from the active to the listen state is on the order of nanoseconds, according to Table II, and, thus, the rate R_{a2l} is not considered in the model. In case of packets' arrival during d_{listen}, the ONU goes back to the active state in nanosecond time (similarly to R_{a2l}, the rate R_{l2a} does not considered in the model), otherwise it transits from the listen to the sleep state. In practice, d_{listen} is the parameter of the $\mathcal{EPON}_{\mathcal{CT}}$ model that determines the condition that triggers the sleep state. A long listen period would deteriorate energy saving, but too short periods would force the ONU to make early transitions to the sleep state increasing the packets' delay.

According to [3], the listen to sleep transition takes $2.88\mu s$ which is the time required by the ONU to turn off its transceivers. This implies that $R_{l2s} = 1\,000/2.88$. When the d_{listen} expires, the ONU transits to the sleep state for a period of d_{sleep} duration, which defines the rate to stay in the sleep state, i.e., $R_{s2s} = 1/d_{sleep}$. During this period, the received downstream packets can either be buffered or ignored. Our model implements a finite queue for packets' buffering. Upon d_{sleep} expiration, the ONU needs a significant amount of time, i.e., $2ms$, to turn on its transceivers and to synchronize with the network [3], [4], [11]. In case of packets' arrival during d_{sleep}, the ONU transits from sleep to active, with the rate R_{s2a}, otherwise, from sleep to listen, with the rate R_{s2l}. Both rates are equal to $1/2$. Sleep state duration severely affects the trade-off under consideration, since short sleep periods benefit the packets' delay, but they limit the potential energy saving.

TABLE II
AVERAGE TRANSITION TIMES FOR ONU STATE TRANSITIONS [3], [4], [11]

current/next	active	listen	sleep
active	-	ns	-
listen	ns	d_{listen}	$2.88\mu s$
sleep	$2ms$	$2ms$	d_{sleep}

The elements of Table I and II are included in the proposed $\mathcal{EPON}_{\mathcal{CT}}$ model, indicating that the finite state machine of the ONU is synchronized with the ONU-OLT communication under EPONs specifications. Once the transitions' rates have been precisely defined, the goal is to properly tune the d_{listen} and d_{sleep} parameters in order to adjust the trade-off between QoS requirements, in our case the packets' delay, and the desirable energy saving.

V. RESULTS

We employ the PRISM model checker [20] for the design of the $\mathcal{EPON}_{\mathcal{CT}}$ Markov model. Once the model is built, model checking enables the verification of the EPON's properties. We use properties of the form $\mathcal{P}_{=?}(\phi)$ to evaluate the probability of some path to satisfy ϕ. This way we can compute the probability of certain events. In addition, we use both instantaneous and cumulative reward properties, described in Section III-B, to derive the expected packets' delay and the expected energy saving, respectively.

The proposed $\mathcal{EPON}_{\mathcal{CT}}$ model mastered by the downstream transmission of a number of $packets$. Thus, at a first place, it is desirable to measure the probability that all $packets$ will be transmitted by the OLT and received by the ONU in a certain amount of time. Apparently, time (ms) depends on the network parameters, i.e., the packets' arrival rate λ, the rate of the downlink channel C, as well as the packets' length L ($\mu = C/L$). We use the property $P = ?\ [F \leq C_0\ finish]$, in order to find final states before C_0, for which the formula "finish" will be true. This formula represents the boolean expression which controls that all $packets$ have been transmitted and received successfully.

Results, for $packets = 1000$, are depicted in Fig. 3, where curves corresponding to higher arrival rates reach probability 1, while those of $\lambda = 0.4$ and 0.2 depict that verification has been completed by 98% and 44%, respectively, for $C_0 = 50\ ms$. This indicates that formula "finish" will eventually become true, but, as it is expected, the curves shift to the left with the increase of λ, denoting that model concludes sooner. In Fig. 3, we define listen and sleep periods equal to $2\ ms$

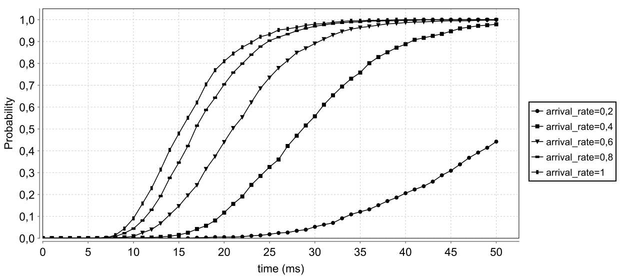

Fig. 3. Probability of OLT transmitting a number of packets (1 000) successfully for different packet arrival rates λ

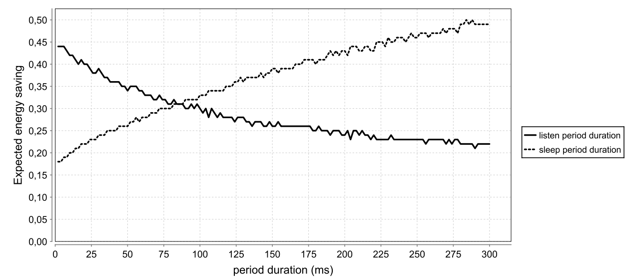

Fig. 5. The impact of listen and sleep period duration (ms) over the expected energy saving when packet arrival rate is $\lambda = 0.3$

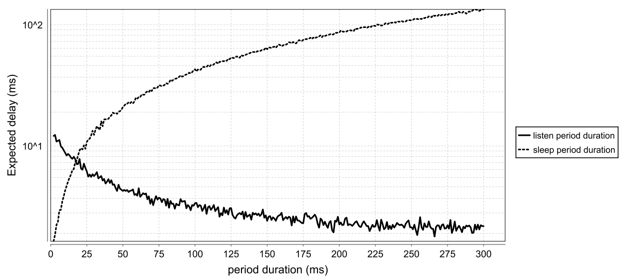

Fig. 4. The impact of listen and sleep period duration (ms) over the expected delay (ms) when packet arrival rate is $\lambda = 0.3$

and 4 ms, respectively, and, it is reasonable that, this way, we cause extra delays in the model.

Since listen and sleep states, introduced at the ONU side for energy saving, cause delays in packets' exchange, they should be configured to tune this trade-off. Hereafter, our model provides quantitative results to demonstrate the impact of d_{listen} and d_{sleep} parameters on the cost metrics. In particular, we derive the energy saving percentages putting the ONU into the sleep state, while satisfying certain levels of delay.

For the delay performance, our model is augmented with a reward which counts queuing and transmission delay as well as the "wait-to-wakeup" delay [5], [15]. The packets that arrive while the ONU is sleeping, they have to wait until it wakes up. The average waiting time equals to $d_{sleep}/2\ ms$, i.e., half the sleep period duration, and is defined as "wait-to-wakeup" delay [5], [15].

Fig. 4 demonstrates that delay decreases with the increase of the listen period duration (d_{sleep} is fixed at 20 ms). This is owed to the decrease of the sleep state probability P_{sleep}. The "wait-to-wakeup" time causes longer delays for packets arriving during the sleep state compared to those arriving during the active or listen state. Thus, the decrease of P_{sleep} entails the decrease of the average expected delay. On the contrary, delay increases with the increase of the sleep period duration (d_{listen} is fixed at 8 ms), since "wait-to-wakeup" time dominates the overall delay. In Fig. 4, d_{listen} and d_{sleep} are changed to cause delay of 10 up to 100 ms, which characterize voice and video traffic classes, correspondingly [21].

Then, based on Fig. 4, we study the impact of d_{listen} and d_{sleep} on the expected energy saving. For d_{sleep} changing, we define $d_{listen} = 8\ ms$. We picked the minimum value which causes delay of 10 ms (according to Fig 4), since, intuitively, higher values of listen period lead to the increase of power consumption. Looking at ONU's finite state machine, Fig. 2, it is expected that increasing the time the ONU stays in listen state and providing the option to interrupt that period going back to the active state in case of packets' arrival, we will have many transits between active and listen states (major power consumers). In Fig. 5, we observe how the expected energy saving is increasing with the increase of d_{sleep}. Obviously, the more the ONU getting to sleep the higher the benefit in terms of energy saving.

But, which is the threshold of d_{sleep}, so that not only gaining in energy saving but at the same time taking care of performance constraint, i.e., delay? Fig. 4 provides us with the maximum value of d_{sleep} which causes delay of 100 ms. Fixing $d_{sleep} = 200\ ms$, we notice how the expected energy saving is decreasing with the increase of d_{listen}.

Fig. 4 and 5 clearly demonstrate how the parameters of listen and sleep period durations compete each other over the trade-off between the energy saving and delay. In particular, Fig. 4 provides the configuration $(d_{listen}, d_{sleep}) = (8\ ms, 20\ ms)$ for delay equal to 10 ms, which is verified by the Fig. 6. The curve denoted as voice traffic shows, indeed, that the delay is less than 10 ms for low arrival rates and slightly increases as λ becomes greater than 0.5. Having chosen a short sleep period, the overall average delay is dominated by the queuing delay, which increases with the increase of the traffic rate. On the contrary, the curve denoted as video traffic expresses the delay caused when $(d_{listen}, d_{sleep}) = (4\ ms, 200\ ms)$. In this case, we achieve delay less than 100 ms, which gets decreasing with the increase of the arrival rate. With a high value of d_{sleep}, the overall average delay is dominated by the "wait-to-wakeup" delay. But, with the increase of the traffic rate, the sleep state probability decreases, and the "wait-to-wakeup" time also decreases. Therefore, the overall average delay is reduced.

Finally, having achieved the delay constraint for the use cases considered (i.e., voice and video traffic), we can derive the results regarding the potential energy saving that we can expect. Since, our $\mathcal{EPON}_{\mathcal{CT}}$ model is inspired by the sleep control scheme proposed by Zhang *et al.*, it is desirable to contrast it to our solution.

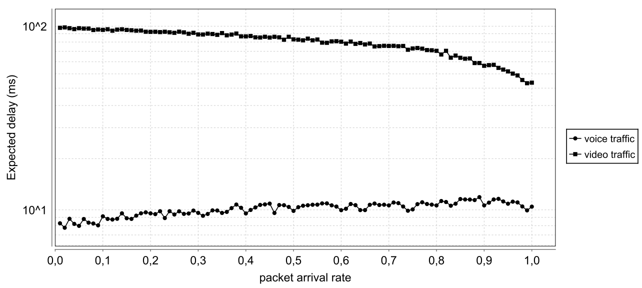

Fig. 6. The expected delay for: i) $d_{listen} = 8ms$ and $d_{sleep} = 20ms$ (voice) and ii) $d_{listen} = 4ms$ and $d_{sleep} = 200ms$ (video)

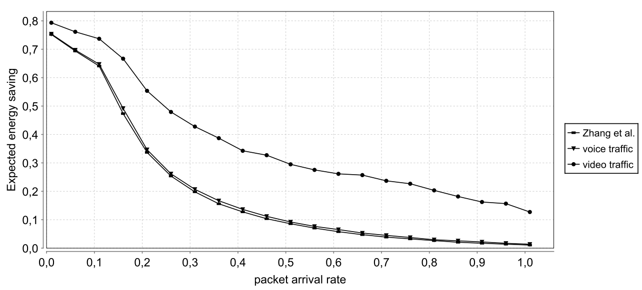

Fig. 7. The expected energy saving for: i) $d_{listen} = 8ms$ and $d_{sleep} = 20ms$ (voice) and ii) $d_{listen} = 4ms$ and $d_{sleep} = 200ms$ (video)

The analysis of Zhang *et al.* [5], [15] prioritize QoS constraint, and, thus, it achieves conservative results, in terms of energy saving, with the increase of the packet arrival rate. For example, it starts with 70% energy saving when the arrival rate equal to 6% of the service rate, but shortly after it drops below 20%, as depicted in Fig. 7. An explanation is that the sleep period is quite short, e.g., up to 20 ms, which entails many transitions among the ONU's states. In fact, apart from the impact in energy conservation, delay impact is also expected, but this is not reflected in their results, since the wake-up time is considered negligible in [5], [15]. Our voice regarding results are very similar to that of [15], since in this case, QoS requirements are quite stringent, i.e., 10 ms delay, and thus short a sleep period is preferable.

However, we observe that, video-traffic results keep the energy conservation at significantly high levels. When the "conservative" policy of the short sleep period, i.e., $d_{sleep} =$ 10 ms, leads to 20% of energy saving, the "aggressive" policy of the long sleep period, i.e., $d_{sleep} = 200$ ms, achieves 43% saving, while it goes down to 20% when the arrival rate equal to 80% of the service rate. This is due to the fact that the QoS constraint, i.e., 100 ms delay, stops being so stringent.

VI. Conclusion

In conclusion, the quantitative results of our formal analysis exhibit the impact of the listen and sleep periods' duration on the trade-off between QoS requirements and desirable energy conservation. Our analysis shows that, when designing an energy-efficiency policy considering sleep state, short sleep periods are suitable if QoS impairments are strict. Otherwise, guided by the QoS constraints and keeping the energy saving as the primary objective, we can arrange long sleep periods. Our future plans include further investigation of the listen and sleep periods' parameters in EPONs with a number of ONUs (e.g., 16 or 32) and software-defined strategies which would dynamically adapt such parameters to the network conditions and users' requirements.

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