Evaluating Energy Efficiency of ONUs Having Multiple Power Levels in TDM-PONs

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***Abstract*—A TDM Passive Optical Network (TDM-PON) proposes the use of sleep modes for Optical Network Units (ONUs) to maximize Energy Efficiency (EE). When an ONU manages a sleep mode, it needs to turn on and off some of its components based on communication requirements. Hence, an ONU ends up with multiple power levels. Existing analytical models for evaluating EE consider that an ONU has only two power levels. However, we have found in some literature where an ONU can have more than two power levels. In this letter we propose an analytical model to quantify the EE of an ONU having more than two power levels. We demonstrate the accuracy of the model by means of simulation under two different sleep interval deciding algorithms.**

***Index Terms*—TDM-PON, energy efficiency, sleep mode.**

I. INTRODUCTION

THE design of energy efficient networks is becoming an urgent necessity due to the rise of the energy costs and the associated ecological impact produced by ICT equipment. A common metric to measure the Energy Efficiency (EE) of a network is the bit/energy (b/J) [1]. This parameter allows us to quantify the EE of a network as well as to identify the improvement when applying a novel proposal [1]. Thus, in this letter we aim to develop a comprehensive analytical model to measure the energy consumption (and in conjunction, the EE) of an Optical Network Unit (ONU) with multiple power levels in a TDM Passive Optical Network (TDM-PON).

The ITU-T recommends Cyclic sleep and Doze mode for ONUs of Ten Gigabit PON (XG-PON) [2]. In the *Asleep state* of Cycle sleep mode both the Transmitter Module (TM) and Receiver Module (RM) of an ONU are off. Apart from that, in other states an ONU keeps both TM and RM on. Similarly, in Doze mode only in *Listen state* TM is turned off, while in all other states both the TM and RM are kept on. Thus, each of these sleep modes an ONU has two power levels. Similarly, authors in [3], [4] consider two states for an ONU: *Active state* and *Sleep state*. They consider that both TM and RM are on in *Active state*, while in *Sleep state* both are off.

The proposals in [5], [6] suggest that components of an ONU should be deliberately turned off whenever they do not have any function to perform. Authors in [5], [6] propose four states for an ONU. They suggest both TM and RM should be on when an ONU needs to transmit and receive both. In addition, when there is only uplink communication is required, only TM should be turned on. Conversely, only RM is switched on when there is downlink communication is needed exclusively. Finally, both TM and RM should be put off when there is no communication between the Optical Line Terminal (OLT) and an ONU. Therefore, an ONU in their solution ends up with four power levels. Currently, we can find that some ONU manufacturers (e.g. [7]) provide option for turning on or off both TM and RM purposely in an ONU. Undeniably, turning on a particular module based on only its communication requirements can lead towards further energy saving in ONUs. Section III presents significance of this.

To measure energy consumption of an ONU, up to now, existing analytical models (e.g. [3], [4]) solely consider two power levels (both TM and RM are on or both of them are off). However, to the best of our knowledge to date there is no analytical model available for quantifying EE when an ONU has more than two power levels.

In this letter, we propose an analytical model for evaluating EE of an ONU having four power levels when it manages sleep mode. This analytical model takes into account performance influencing parameters such as: downlink sleep interval length, uplink polling cycle length and PON synchronization time (t_o) which is required after waking up from *Sleep state* [4].

II. ENERGY EFFICIENCY MODELING

In this section, in the light of existing proposals we first discuss some considerations that we take into account to build an analytical model. Later, we describe our analytical model that ends up in a final equation to evaluate the EE of an ONU with four power levels.

A. System Model

Apart from the TM and RM, an ONU has other components (e.g. digital circuitry) [4]. In this letter, we call all other components (i.e. components excluding TM and RM) as Common Modules (CMs). These CMs need to be always on regardless an ONU's state and their total power consumption, defined as P_{CM}, is 0.7 W [9]. Similar to [5], [6] we assume that an ONU turns on RM and TM only when they have certain function to perform. Note that both TM and RM have two possible positions (i.e. on or off). Then, there will be four binary combinations based on the positions of TM and RM. Therefore, in our model, we consider that an ONU has

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TABLE I
NOTATIONS USED IN ANALYTICAL MODELING

Notations	Meaning
L	Sleep-interval Related Signaling (SRS) completion time.
t_{pl}	Polling Related Signaling (PRS) completion time.
Tc	Uplink polling cycle length of a TDM-PON.
T_{slot}	Length of uplink transmission duration in a Tc for an ONU.

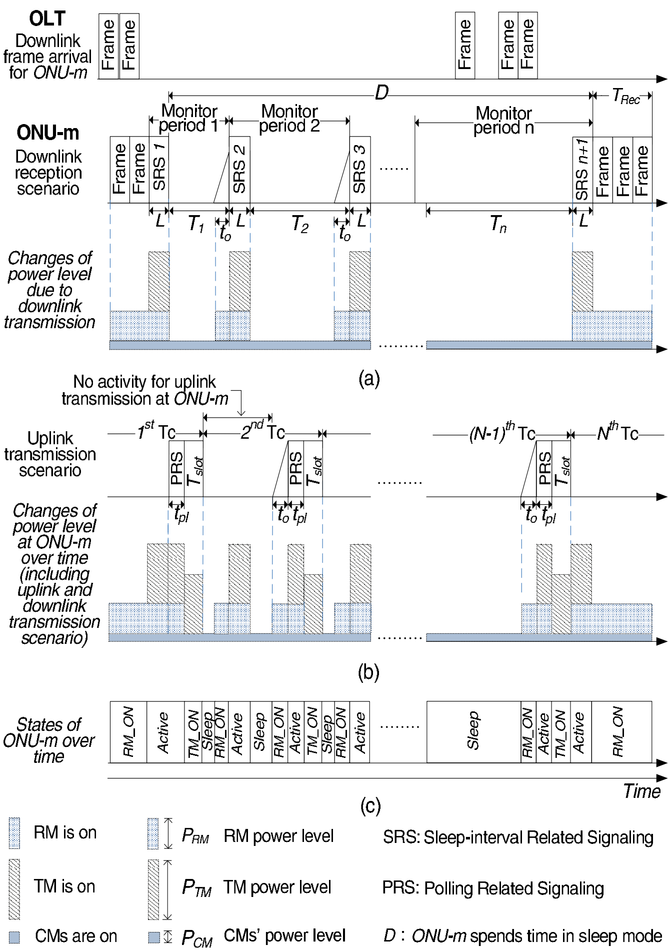

Fig. 1. Uplink and downlink transmission scenarios: (a) downlink transmission and changes of power level over time; (b) uplink transmission and change of power level over time; (c) states of *ONU-m* over time.

four power levels. In addition, we consider that an ONU implements four states during sleep mode operation; *Active state* (all components are on), *RM_ON state* (RM and CMs are on), *TM_ON state* (TM and CMs are on), and *Sleep state* (only CMs are on). In the *RM_ON state*, an ONU consumes 1.7 W [9]. These numbers imply that the RM power consumption, defined as P_{RM}, is 1 W (= 1.7$-P_{CM}$). When an ONU is in the *Active state*, it consumes 4.69 W [9]. Hence, the power consumed by TM, expressed as P_{TM}, is 2.99 W (= 4.69 $-P_{RM}-P_{CM}$). Besides, Table I includes a set of notations along with their meaning that we will be using in this letter to describe our analytical model.

As proposed in [3], [8], we assume in our model that when an ONU does not have anything to receive the OLT computes the sleep interval using an algorithm (we explain this in Section III). Then, the OLT initiates SRS with that ONU, as shown in Fig. 1(a). Basically, an SRS process includes a notification message to the ONU that carries the duration of the next (e.g. *jth*) sleep interval (T_j). That notification message could also request the targeted ONU to keep its RM on in case the OLT has any frame to transmit. In turn, the ONU sends back an acknowledgement message to the OLT [4]. Therefore, during an SRS an ONU needs to turn on both the RM and TM. After an ONU receives the sleep interval T_j, it wakes up after that time and conducts a new SRS during a time interval of length *L*. Therefore, the final length of the *jth* sleep cycle is computed as T_j+*L*. If the OLT has any frames for that ONU, the OLT invokes the ONU to keep the RM on through the SRS. Otherwise, the OLT requests the targeted ONU to turn off the RM and indicates the *j+1th* sleep interval T_{j+1} (see Fig. 1(a)). We assume $T_j \leq T_{j+1}$.

When an ONU dispenses sleep mode, it might need to wake up due to arrival of uplink traffic from user premises. Hence, it is considered in [2], [8] that the OLT assigns consistently a minimum amount of uplink slot to each sleeping ONUs in each Tc. By doing so, a sleeping ONU can initiate PRS for getting an uplink transmission slot from the OLT. As these solutions propose to manage sleep mode in ONUs taking into account downlink traffic only, we refer to them as Downlink Based (DB) solutions. Here, our model assumes that a T_{slot} is followed by a PRS. During a PRS process time (t_{pl}) an ONU needs to be in *Active state* (i.e. both the RM and TM are on) to send a bandwidth request and get a grant message from the OLT with the bandwidth allocation.

B. Analytical Model to Obtain Energy Efficiency

Considering the system model presented in Section II.A, we develop an analytical model to obtain EE of an ONU in this sub-section. For the downlink transmission case, we assume that the *ONU-m* goes to *Sleep state* n number of times and spends D amount of time in different states before receiving a downlink frame. Therefore, D accumulates n sleep cycles. Let e_j represents the event meaning that there is at least one frame arrival during the *jth* monitor period for the *ONU-m*. Then $Pr(e_j = \mathit{true}) = 1 - e^{-\lambda_m (T_j + L)}$, where λ_m is the downlink frame arrival rate for the *ONU-m* and it follows Poisson process as considered in [8]. Then the probability of having *jth* sleep interval ($Pr(n = j)$) is Pr (*no frame arrivied in monitor period* 1, 2,.., $j-1$) Pr(*at least* 1 *frame arrived during jth monitor period*) and it is expressed as follows [10]:

$$Pr(n = j) = e^{-\lambda_m \sum_{i=1}^{j-1} T_i + L} \left(1 - e^{-\lambda_m (T_j + L)}\right). \qquad (1)$$

The average time spent in sleep mode by the *ONU-m* before receiving a frame from the OLT can be expressed as $E[D] = \sum_{j=1}^{\infty} Pr(n = j) \sum_{k=1}^{j} (T_k + L)$ [10]. Then, the average number of sleep cycles that the *ONU-m* has during $E[D]$ is expressed as $E[n] = \sum_{j=1}^{\infty} j Pr(n = j)$ [10]. This implies that there are $E[n]$ number of SRSs during $E[D]$. Besides, one additional SRS is required to put *ONU-m* into *Sleep state* (i.e. SRS 1 in Fig. 1(a)). During each sleep cycle (e.g. T_j+*L*) the energy will be spent due to: CMs power consumption, PON synchronization, and the SRS (see Fig. 1(a)). The expression to compute the average energy spent during $E[D]$ is thus expressed as $\varepsilon_{E[D]} = \sum_{j=1}^{\infty} Pr(n = j) \sum_{k=1}^{j} ((T_k + L)P_{CM} + (t_o + L)P_{RM} + LP_{TM})$.

Next, we want to measure the energy spent from the time in which the first SRS (i.e. SRS 1) is conducted (to switch the *ONU-m* into *Sleep state*) to the time when the *ONU-m* receives the last frame from the OLT after waking up. We can obtain the total energy expenditure (ε_{DL}) by summing the energy spent during: the SRS 1, $E[D]$ and the reception time of arrived frames for the *ONU-m* at the OLT during $E[D]$+L. The reception time (T_R) for the frames that arrive during $E[D]$+L is $((E[D] + L)\lambda_m F_s)/L_R$, where F_s is the average frame size and L_R is the uplink/downlink transmission rate. Then, $\varepsilon_{DL} = L(P_{CM} + P_{RM} + P_{TM}) + \varepsilon_{E[D]} + T_R(P_{CM} + P_{RM})$. Based on ε_{DL}, the total amount of energy spent during an observation period (T_b) is calculated as follows:

$$\varepsilon_{T_b,DL-m} = (T_b/(L + E[D] + T_R))\, \varepsilon_{DL}. \quad (2)$$

After measuring the energy consumed in the downlink, we focus on the energy consumption in the uplink transmission. Fig. 1(b) shows that during a *Tc* the *ONU-m* spends times for PRS process (t_{pl}) and T_{slot}. In addition, the *ONU-m* needs to spend time for PON synchronization before the PRS. However, if there are some activities going on within the downlink related to the *ONU-m* (e.g. SRS, downlink frame reception) at that moment, it does not need to spend time for PON synchronization. This implies that the *ONU-m* must spend time (i.e. t_o) to get PON synchronization for uplink transmission if it needs to switch from *Sleep state*. For example, if we look at the Fig. 1(b), during the 1^{st} *Tc*, *ONU-m* does not need to get any PON synchronization before initiating PRS because at that moment *ONU-m* is already involved in SRS staying in *Active state*. Whereas, during the 2^{nd} *Tc* the *ONU-m* needs to gain PON synchronization before PRS because the *ONU-m* is in *Sleep state* at that moment. Then, there will be many cases where the *ONU-m* needs to perform PON synchronization before PRS in case it is in *Sleep state*. It can be observed from the Fig .1(a) that from the starting point of SRS 1 to the time when the last downlink frame is received by the *ONU-m* (i.e. $L + E[D] + T_R$), there are activities for downlink transmission during the SRS 1, $E[n](L + t_o)$ and T_R. Then, next equation provides the probability that the *ONU-m* is in *Sleep state*:

$$Pr_{SS} = 1 - \frac{L + E[n](L + t_o) + T_R}{L + E[D] + T_R}. \quad (3)$$

Note that from the uplink transmission perspective the period showing a no activity region during *Tc* is *Tc*-$t_{pl}$$-$$T_{slot}$$-$$t_o Pr_{SS}$. We do not need to add any extra energy for this region because the amount of energy spent during this time has been already counted in *Eq.* (2). Moreover, in the subsequent equation for the uplink energy consumption, we do not add the energy consumed by CMs during T_{slot} and t_{pl} in the given observation period T_b, because it was already taken into consideration in the earlier equations. Then, the expression to compute the amount of energy spent during a *Tc* is $\varepsilon_{UL} = (t_o Pr_{SS} P_{RM} + t_{pl}(P_{TM} + P_{RM}) + T_{slot} P_{TM})$. Then, the total amount of energy spent for uplink transmission associated with the *ONU-m* during T_b is given by:

$$\varepsilon_{T_b,UL-m} = (T_b/Tc)\, \varepsilon_{UL}. \quad (4)$$

Here, we sum up the total transmitted and received bits by the *ONU-m* during T_b.

$$A_{ONU-m} = T_b \lambda_m Fs + (T_b/Tc)\, T_{slot} L_R. \quad (5)$$

Once we have calculated the total amount of transmitted and received bits using *Eq.* (5), and the total energy consumption for both downlink and uplink using *Eq.* (2) and *Eq.* (4) respectively for an ONU having four power levels, it is simple to find the EE of an ONU. For that, we just need to sum up total transmitted and received bits by *ONU-m* during the T_b and then divide it by the total spent energy associated with *ONU-m* during that time. The EE of an ONU (e.g. *ONU-m*) with four power levels is thus obtained as follows:

$$EE_{ONU-m} = (A_{ONU-m}/(\varepsilon_{T_b,DL-m} + \varepsilon_{T_b,UL-m}))\,. \quad (6)$$

III. Performance Evaluation

We validate the proposed model to compute the EE of an ONU with four power levels under two different algorithms to decide ONUs' sleep interval. Toward this end we compare analytical results with simulation results (we use a C++ discrete event simulator developed in our work). The first algorithm is the Fixed Sleep Interval (FSI) [8]. In FSI, the OLT always assigns a fixed sleep interval *Ts* in absence of downlink frames for an ONU. The second algorithm is the Exponentially Incrementing Sleep Interval (EISI) [3]. This algorithm proposes that the length of the sleep interval of an ONU can increase exponentially after each SRS process from an initial sleep interval (*Tmin*) until a maximum value (*Tmax*) if no downlink frames arrive for that ONU at the OLT. EISI selects the *jth* sleep interval following the policy, $T_j = min$ $\{Tmax\,,\, A\}$, where $A = (2^{j-1}Tmin)$. We consider $Ts = Tmin$ in our performance evaluation. Besides, here we present results that show how number of power levels and communication overhead influence EE of an ONU.

We use the following parameters in our evaluation: L_R = 1 *Gbps*, $F_s = 1518$ bytes, $t_{pl} = 0.2\ ms$, $L = 1.6\ ms$ [8], *Tmax* = $50\ ms$ [5], $T_b = 1000\ ms$, and number of ONUs per OLT is 32. We assume that the utilization of T_{slot} is a 100% and there is no frame loss between the OLT and an ONU. Since $t_o = 2\ ms$ [3], [5], in order to let an ONU stay in *Sleep state* at least 1 ms we establish *Tmin* $\geq 3\ ms$. Fig. 2(a) and (b) show the EE from a wide set of arrival rates for the FSI and EISI respectively. In addition, these figures show the FSI and EISI EE results for different values of *Tmin* and *Tc*.

As depicted in the Fig. 2(a) and (b) our model is very accurate since it matches the simulation results. Fig. 2(a) (FSI) shows that as the downlink arrival rate increases EE decreases up to $\lambda = 0.2\ frames/ms$. This occurs because the total amount of transmitted and received bits at an ONU does not significantly increase for the increment of λ across the low arrival rate region (e.g. $\lambda \leq 0.2\ frames/ms$). However, the energy expenditure increases significantly due to the increment in the number of SRSs. Fig. 2(b) (EISI) follows a similar behavior. However, in this case the drop of EE from $\lambda = 0.001\ frames/ms$ is sharper than that of EE in Fig. 2(a). This happens because in very low arrival rate regions EISI allows an ONU to have longer sleep intervals (i.e. no frame arrives, hence sleep interval increases). Therefore, the number

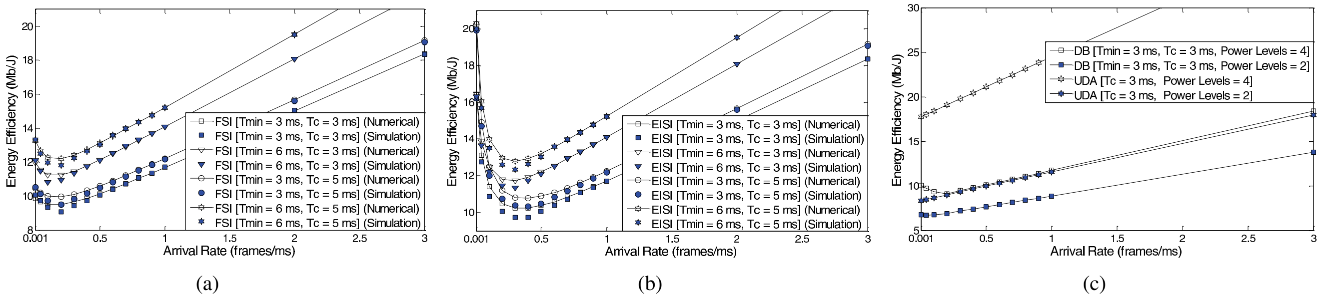

Fig. 2. (a) Energy efficiency of an ONU with four power levels when using FSI; (b) energy efficiency of an ONU with four power levels when using EISI; (c) influence of different power levels and control messages related overhead on ONU's energy efficiency.

of SRSs is small during T_b. However, as λ slowly increases the frequency of performing SRSs in an ONU increases while the total received and transmitted bits do not increase much over the low arrival rate region (e.g. $\lambda = 0.001$ to 0.4 $frames/ms$). For example, at $\lambda = 0.33$ $frames/ms$, one frame will ideally be received by a given ONU after the completion of each first sleep interval when *Tmin* $= 3$ ms. In contrast, even though an ONU cannot increase its sleep interval in EISI when it starts receiving frames after the completion of each sleep cycle, EE increases as λ grows up (i.e. $\lambda > 0.33$ $frames/ms$). Likewise, in FSI, EE grows up as λ increases after a certain point.

A similar behavior is also observed when *Tmin* $= 6$ ms in Fig. 2(a) and (b). However, *Tmin* $= 6$ ms provides better EE than the EE when *Tmin* $= 3$ ms. That happens because when *Tmin* $= 6$ ms the frequency of conducting SRS is much lower than in the earlier case. However, each downlink frame will experience more delay when *Tmin* $= 6$ ms than for *Tmin* $= 3$ ms. We can observe the clear influence of *Tmin* on downlink frames delay in [3]. Besides, we can also notice that *Tc* has impact on EE from Fig. 2(a) and (b). As *Tc* increases, EE grows up. The reason to explain this is that an ONU performs less number of PRSs during T_b when *Tc* increases. Ironically, a large *Tc* provides better EE at the price of increasing uplink frame delay as they are buffered for a long time at an ONU.

Figure 2(c) depicts the influence that (i) the number of power levels of an ONU, and (ii) the overhead of control messages (e.g. SRS in DB solutions) have on EE (results obtained through simulation). Unlike DB solutions (based on which the analytical model is proposed in this letter), we can find in the literature some solutions (e.g. solutions in [6], [11]) that only use a single pair control message in one polling cycle (*Tc*). This is possible because these solutions are aware of both downlink and uplink traffic status together. We refer to these solutions as Uplink and Downlink Aware (UDA) solutions.

In relation to the number of power levels, Fig. 2(c) shows that an ONU with four power levels is more energy efficient than an ONU having only 2 power levels independently on whether they are operated under DB or UDA. This is because an ONU with four power levels deliberately turns off its components whenever their tasks are completed. In contrast, an ONU with two power levels uses both TM and RM irrespective to uplink and/or downlink transmission requirement. Besides, the results in the figure exhibit that UDA leads to a better EE than DB. This happens because UDA has less control messages compared to DB, thus reducing the associated overhead. Hence, an ONU operated under UDA solutions spends more time in *Sleep state* than an ONU in DB solutions.

IV. Conclusion

This letter has proposed a comprehensive analytical model to calculate the EE of an ONU with four power levels in a TDM-PON. To the best of our knowledge this is the first model that takes more than two power levels into consideration. We have also demonstrated that our model is very accurate by means of simulation. In particular, we have applied our model to two well-known algorithms that are used by an OLT to compute the sleep interval duration of an ONU. In both cases our analytical model provides EE values that are very close to the simulation results. Besides, we have demonstrated successfully in this letter that control messages associated overhead has substantial influence on EE of an ONU and four power levels leads to a significant improvement in EE of an ONU as compared to two power levels.

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