

Sleep Mode for Energy Saving PONs: Advantages and Drawbacks

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Abstract— A common approach to reduce energy consumption in communication networks is to allow network elements to switch to sleep mode. While this technique has been widely utilized in wireless networks, recent studies have proposed to exploit sleep mode in wired networks to conserve energy as well. This paper focuses on some feasible implementations of sleep mode in passive optical networks (PONs). In particular, ONU sleep mode is considered. The paper first outlines the ONU wake-up process using current time division multiplexing (TDM) PON protocols. Current and novel optical network unit (ONU) architectures that selectively switch-off some elements are then described. Their advantages in terms of energy savings are analytically computed under different traffic scenarios. Using the proposed architectures, analytical results show more than 50% energy saving under realistic TDM traffic. Finally, possible drawbacks in terms of new scheduling challenges are also discussed and potential solutions are presented.

Keywords- TDM-PON; sleep mode; synchronization; clock recovery; power and energy consumption.

I. INTRODUCTION

Recently, there has been a global attention to lower energy consumption in many fields and data communications networks are part of them [1]. Commonly, to reduce energy consumption in communications networks, nodes are allowed to switch to sleep mode when they are idle and to wake-up when they need to either send or receive data. Such approach has been widely exploited in wireless networks and, in particular, in wireless sensors networks, where saving node's battery power is of paramount importance [2].

Studies have proposed to apply the approach of allowing nodes to switch to sleep mode also to fixed IP router-based backbone networks. In [3,4], it is shown that energy can be conserved by selectively turning off spare IP router interfaces or routers whose capacity is not required to transport off-peak traffic. The approach proposed in [3,4] exploits the capability of IP protocols to automatically reroute packets once router interfaces or entire routers are down. However, routers must be made capable of quickly switching back to working mode (i.e., wake-up) if traffic demand increases. Similar studies are also proposed to focus on reducing communications network energy consumption in metro and access networks [5-7]. Finally, the importance of lowering energy consumption in Ethernet based access networks is witnessed by the set up of the IEEE P802.3az Energy Efficient Ethernet Task Force.

This paper addresses the challenge of reducing the energy consumption of passive optical networks (PONs). Most of the studies conducted within both the research community [8] and working groups in the standard bodies [9] build upon the idea of allowing PON network elements, specifically optical network units (ONUs), to switch to sleep mode for saving energy. The concept of such approach stems from the observation that current PONs downstream traffic is broadcast to all the ONUs even though some ONUs have not requested it. Then, data are received by the ONUs if data are destined to them but, otherwise, data are simply discarded. This implies wasting significant energy at the ONU side to always receive data. Energy can be therefore conserved at the ONUs by switching to sleep mode when they do not need to either send or receive traffic.

However, to implement ONU sleep mode, some issues must be solved. In current time division multiplexing (TDM)-Ethernet PON (EPON), ONUs maintain their local clock synchronization with the OLT clock by recovering it through their clock and data recovery (CDR) circuit from a continuous bit stream (data or idle) they receive from the OLT [10-12]. If an ONU stops receiving downstream transmission, ONU clock synchronization is lost and current ONU architecture requires long clock recovery time when the ONU wakes up from the sleep mode. Moreover, the absence of synchronization among different ONUs clocks might cause upstream data collision at the OLT.

The main contributions of this paper are the following. First, the wake-up processes for ONU are described for both Gigabit PON (GPON) and EPON. Then, the power consumption in active mode (i.e., when ONU is up) and sleep mode are compared for ONU with current receiver architecture. In addition, two novel ONU receiver architectures are proposed and their respective power consumption behaviors are studied. The proposed architectures allow ONUs to switch to sleep mode and quickly recover the OLT clock with minimal changes from current ONU design. The effects of sleep mode on the energy saving performance are analytically computed and compared. Results show nearly 80% energy saving performance in light traffic and more than 50% energy saving under realistic TDM traffic. Finally two main issues raised by the introduction of ONU sleep-mode in PONs are discussed: downstream traffic scheduling and ONU clock drift. Some possible solutions are also outlined.

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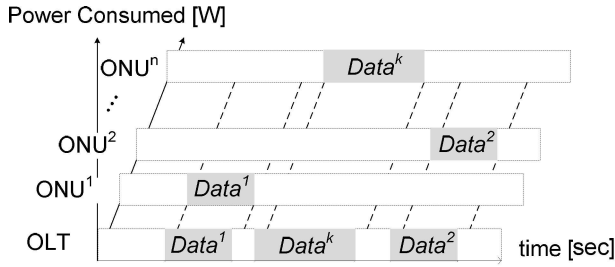


Figure 1.

In energy saving TDM-PON, ONU switch to sleep mode in empty slots.

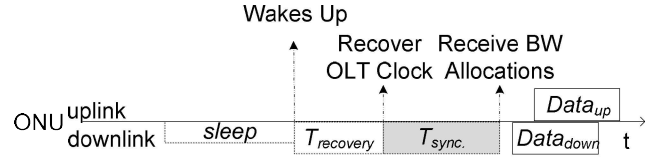


Figure 2.

Illustration of the wake-up process of an ONU waking up from sleep.

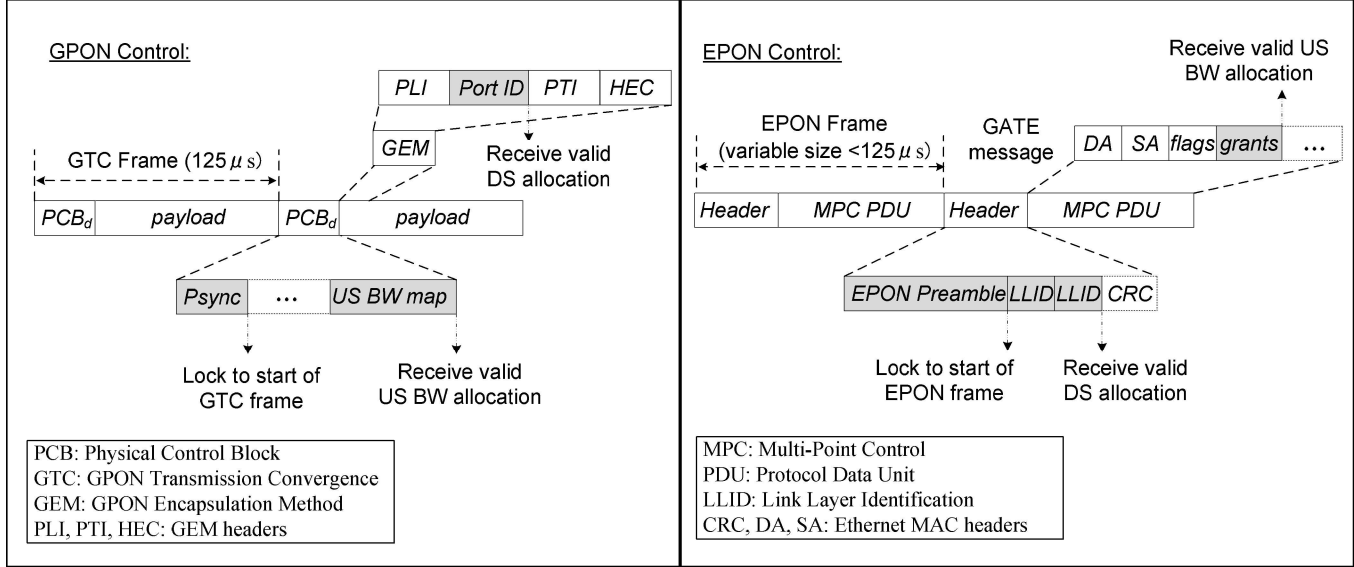


Figure 3. Illustration of GPON and EPON frames and controls that are utilized to implement sleep mode wake-up process.

II. SLEEP MODE AND SYNCHRONIZATION IN TDM-PON

In current TDM-PONs, OLT physically broadcasts downstream traffic to all ONUs that remain active even if they are not the destination of any data. Fig. 1 shows the potential energy savings if the ONUs stay active only in the receiving time slots (i.e., when data are destined to them) (shaded) and switch to sleep mode in empty time slots (white). By exploiting the statistical multiplexing property of the downstream traffic, significant reduction in energy consumption can be achieved.

To enable sleep mode in current TDM-PON, an ONU must wake up from the sleep mode and regain synchronization with the network. Fig. 2 illustrates the necessary phases for an ONU to wake up: the ONU must recover the OLT clock (T_{recovery}) and regain synchronization with the network (T_{sync}). This incurs an overhead, $T_{\text{overhead}} = T_{\text{recovery}} + T_{\text{sync}}$, after which the ONU can listen to the bandwidth allocation and send or receive data again. The synchronization time, T_{sync} , depends on the framing and the MAC protocol utilized. The following subsection assumes the clock has been correctly recovered and details how an ONU could regain synchronization with the network from sleep mode, i.e. synchronization process, utilizing current GPON and EPON framing and control.

A. GPON Synchronizing Process

The GPON transmission convergence (GTC) specifies a GTC frame that lasts 125μs [13], as shown in Fig. 3. At the beginning of each GTC frame, a physical control block (PCB) is inserted, which includes 4 bytes of physical synchronization (Psync) and variable bytes of upstream bandwidth allocation (US BW map). The ONU waking up from sleep mode would use Psync to gain synchronization to the first bytes of the GTC frame. When an ONU wakes up in the middle of an active GTC frame, it would receive a Psync header no later than 125μs plus the 4 bytes (32ns) to synchronize to the GTC frame. Thus, the maximum synchronization delay is no longer than 125μs.

After synchronizing to the GTC frame, the ONU could resume sending or receiving data if it receives an upstream or downstream bandwidth allocation. In GPON, this could be done using either the US BW map field embedded at the end of the PCB or the Port ID field from the GPON encapsulation method (GEM) frame in the ensuing GTC payload section.

B. EPON Synchronizing Process

EPON has much shorter frames than GPON. Each EPON frame comprises only one Ethernet packet, whose the maximum transmission unit (MTU) 1500 bytes, preceded by a

multi-point control (MPC) header. This MPC header includes a preamble that includes a fixed start position delimiter (SPD) to allow ONU to gain synchronization with the start of the EPON frame. Thus, the expected synchronization time in EPON is shorter than the expected time in GPON (125 μ s).

In EPON, multi-point control protocol (MPCP) is used to reserve and allocate bandwidth in the network. After synchronizing to an EPON frame, the ONU could then learn the downstream allocation from the ensuing link layer identification (LLID) field. For upstream bandwidth, the ONU waits for a GATE message that carries its bandwidth grants before sending traffic upstream.

III. ONU RECEIVER ARCHITECTURE OPTIONS

This section first introduces an implementation of sleep mode using current ONU receiver architecture. It then proposes two novel ONU receiver architectures that could significantly reduce the clock recovery time in the wake-up process.

A. Current ONU Receiver Architecture and Sleep Mode

Fig. 4 shows the receiver architecture of current GPON or EPON ONUs, i.e. option 1 ONU receiver. In this architecture, the received optical signal is first converted into electrical signal (i.e., current) by an avalanche photodiode (APD). Two stages of electrical amplifiers, including transimpedance amplifier (TIA) and limiting amplifier (LA), amplify the electrical signal before sending it into the continuous mode CDR (CM-CDR) circuit. The CM-CDR forwards the recovered data and clock to the de-serializer (DMUX). The DMUX then outputs parallelized data to lower speed, back-end digital circuit for further processing. The back-end digital circuit comprises primarily memory and various digital data processing blocks. Specific details of the back-end digital circuit are omitted because their implementations vary.

In this architecture, when an ONU switches to sleep mode, the entire front-end analog circuit and part of the back-end digital circuit are turned off. Some parts of the back-end digital circuit, such as the clock and volatile memory, cannot be turned off and thus the ONU still consumes power during sleep mode. Using power consumption data from a list of well-known PON component vendors, the expected power consumptions during active and sleep mode for option 1 ONU are summarized in table 1.

Option 1 ONU uses CM-CDR to recover the OLT clock when it wakes up from the sleep mode. CM-CDR requires significant time, i.e. 2-5ms [14], to recover OLT clock. As shown in table 2, the long recovery time (T_{recovery}) significantly increases the wake-up overhead that, in turn, degrades the achievable energy saving performance.

B. Proposed ONU Receiver Architecture Option 2

To reduce the long clock recovery time experienced by option 1 ONU receiver, an ONU receiver architecture based on a self-refresh circuit and a burst mode CDR (BM-CDR) is proposed as option 2. Fig. 5 shows the BM-CDR and sleep control circuit that would replace the CDR circuit in option 1, which is highlighted in the shaded box of Fig. 4. The BM-CDR

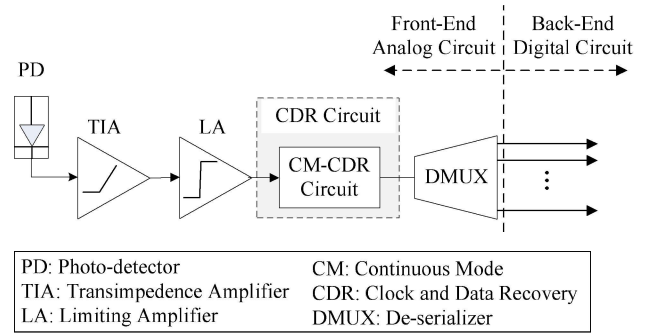


Figure 4. ONU receiver architecture option 1.

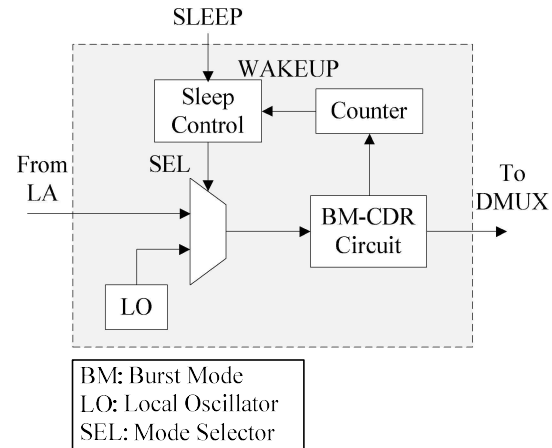


Figure 5. BM-CDR and sleep control circuit for ONU option 2.

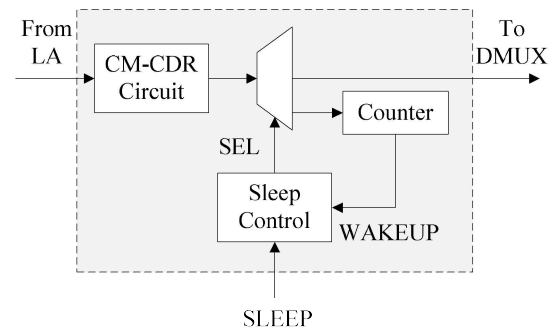


Figure 6. CM-CDR and sleep control circuit for ONU option 3.

circuit uses a local oscillator (LO) to maintain relative clock synchronization with the OLT clock during sleep mode. The relative synchronization can be achieved, for example, if the local clock frequency can maintain within 100 parts per million (ppm) of the OLT clock frequency to satisfy the Ethernet loop timing requirement [10]. When the ONU switches to the sleep mode, sleep mode control receives a SLEEP signal and it selects the LO path instead of the data path as the input to BM-CDR. The counter uses the BM-CDR clock to time the sleep mode. When the counter expires, it sends a WAKEUP signal to the controller and the controller switches back to the data path as the input to the BM-CDR.

Table 1

Power Consumption Comparison for Different ONU Architecture Options

	Front-End Analog Circuit					Back-End Digital Circuit	Total Power Consumption
	APD	TIA	LA	BM/CM-CDR	DMUX		
Active	negligible*	100mW	100mW	330mW †	470mW ▲	2.85W	3.85W (P_{active})
Option 1	off	off	off	off	off	750mW	750mW ($P_{\text{sleep},1}$)
Option 2	off	off	off	on	off	750mW	1.08W ($P_{\text{sleep},2}$)
Option 3	on	on	on	on	off	750mW	1.28W ($P_{\text{sleep},3}$)

* E/G-PON receiver typically consumes a few mW with less than 1mW contributed due to O/E process.

† [14]. Assume negligible power consumption differences between BM and CM-CDR, also assume the sleep mode control and counter circuit consumes negligible power compared to other front-end analog circuit.

▲ See [15].

Table 2

Wake-Up Overhead Comparison for Different ONU Architecture Options

Architecture	Clock Recovery Time* (T_{recovery})	Max Synchronization Time † ($T_{\text{sync.}}$)	Total Overhead (T_{overhead})
Option 1	2-5ms	125μs	5.125ms
Option 2	1-10ns	125μs	125μs
Option 3	none	125μs	125μs

* Time required to perform phase locking operation [14, 16-18].

† Synchronization time required to receive either GATE in EPON or PCB in GPON. Message size of the synchronization pattern is small enough to be negligible compared to the polling time.

The advantage of option 2 ONU is that its clock recovery time can be reduced to as short as 1ns using BM-CDR. Despite leaving BM-CDR circuit on during sleep mode, it only requires small incremental power consumption compared to option 1. This is significant because having a shorter overhead has more potential benefits in terms of energy saving compared to further reducing the power consumption during sleep mode. Another advantage of using BM-CDR is that the incremental cost of incorporating BM-CDR in ONUs is not expected to be high because state-of-the-art BM-CDR relies on the similar semiconductor manufacturing process and materials as CM-CDR.

C. Proposed ONU Receiver Architecture Option 3

A minor drawback of option 2 ONU is that the architecture requires the addition of a precise LO clock. While the cost of such LO clock is not expected to be high, it is often desirable to keep the cost of ONU as low as possible. Thus, an alternative ONU architecture is proposed that does not add any new component to the ONU circuitry.

Fig. 6 shows option 3 ONU architecture. In this architecture, the entire front-end analog circuit is the same as in option 1 ONU architecture, except an additional sleep mode control circuit is placed before the DMUX. Comparing to option 1

ONU architecture, the CM-CDR (as well as the APD photodiode, plus TIA and LA circuit) circuit is left on to maintain accurate accuracy with the OLT clock while the DMUX is switched off during sleep-mode. The sleep control circuit selects the counter data path when the ONU enters into the sleep mode. The counter uses the recovered clock to time the sleep mode. When the counter expires, it sends a WAKEUP signal to the controller and the controller switches the recovered clock and data to the DMUX to resume receiving mode.

IV. ENERGY SAVING PERFORMANCE EVALUATION

The energy saving performance of the three ONU receiver architecture options are analytically computed and compared in this section. The energy consumed by an ONU given some observation period, $T_{\text{observe}} = T_{\text{active}} + T_{\text{sleep}}$, could be found as the sum of energy spent in active mode plus that in sleep mode:

$$E_{\text{ONU}} = T_{\text{active}} \cdot P_{\text{active}} + T_{\text{sleep}} \cdot P_{\text{sleep}} \quad (1)$$

Data of P_{active} and P_{sleep} from table 1 are used in the analysis.

The following subsections present the energy saving performance for each ONU architecture options under two different traffic scenarios. The first scenario considers traffic from the perspective of a single ONU, where the ONU periodically wakes up to send and/or receive data for a fixed

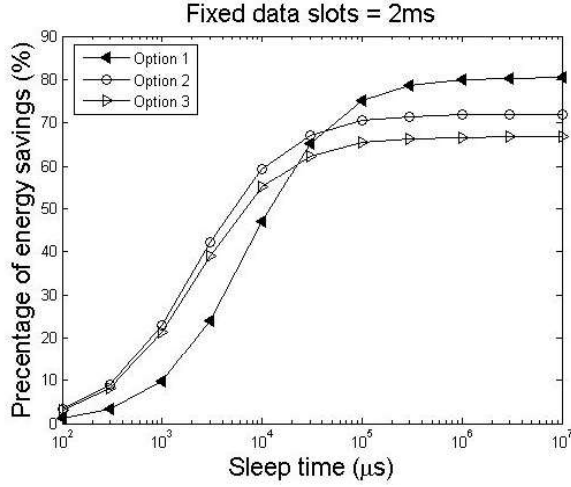


Figure 7. Performance comparison of sleep mode against sleep time.

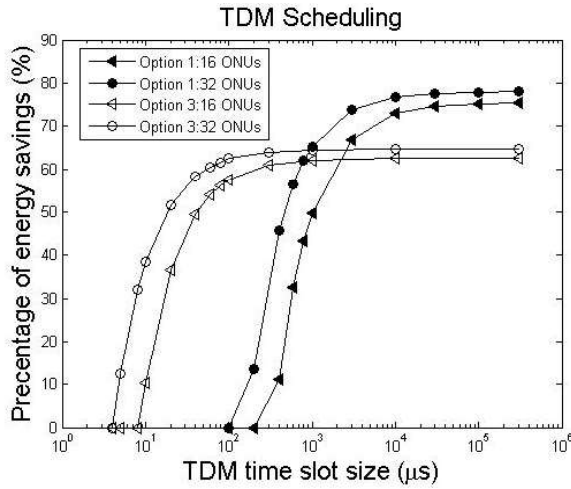


Figure 8. Performance comparison of sleep mode against TDM slot size.

period of time. In this scenario, T_{sleep} is parameterized and $T_{\text{active}} = 2\text{ms} + T_{\text{overhead}}$. T_{overhead} data are extracted from table 2 for the analysis.

The second scenario considers traffic for across all ONUs. The traffic is scheduled using fixed TDM, where each ONU^k turns on to send and/or receive data for a fixed period of time $T_{\text{active}}^k = T_{\text{slot}}^k + T_{\text{overhead}}$. Each TDM cycle is then defined by equation (2).

$$T_{\text{cycle}} = \sum_{k=1}^N T_{\text{slot}}^k \quad (2)$$

In this scenario, the slot size T_{slot}^k is assumed to be the same for all ONUs and this T_{slot} is parameterized in the analysis. With this setup, the amount of time that an ONU spends in the sleep mode could be found by equation (3).

$$T_{\text{sleep}} = T_{\text{cycle}} - T_{\text{active}} = (N - 1) \times T_{\text{slot}} - T_{\text{overhead}} \quad (3)$$

In the subsequent analysis, the energy saving performance is presented using percentage of energy savings, η_{savings} , compared to the energy consumed by the same network without sleep mode using formula (4).

$$\eta_{\text{savings}} = \left(1 - \frac{E_{\text{ONU}}}{T_{\text{observe}} \times P_{\text{active}}}\right) \times 100\% \quad (4)$$

A. Energy Saving Performance Analysis for Single ONU

Fig. 7 shows the results for this analysis. Option 1 ONU saves the most energy when the sleep time is much longer than the data transmission time. This is expected because option 1 has the least power consumption among the three options. On the other hand, option 2 and option 3 ONUs outperform option 1 ONU when sleep time is less than 30ms. This is because the overhead time, T_{overhead} , for option 1 ONU becomes significant with respect to the sleep time. The performance difference between option 2 and option 3 ONUs is small.

The finding suggests that option 1 ONU, which uses current ONU design, provides significant power saving when the ONU goes into sleep for a long period of time. This characteristic could be helpful when an ONU enters into a stand-by mode in which the ONU knows for certain that it will be off-line for some period in advance. In many cases, however, an ONU would not know about its future traffic demand and the ONU would need to wake up more often to learn about possible traffic allocations. In these situations, option 2 and option 3 ONUs are far more desirable. In Fig. 7, for example, option 2 and option 3 ONUs provide more than 10% energy saving than option 1 when sleep time is between 1ms to 10ms.

B. Energy Saving Performance under TDM Traffic

Under a TDM scheduled traffic scenario, an ONU sends and/or receives traffic periodically and waits for a full TDM cycle in which all the other ONUs send and/or receive traffic. In this analysis, option 3 ONU is used to compare against option 1 ONU. Performance of option 2 ONU is omitted because it had shown very similar (and marginally better) performance than option 3 ONU. The analysis considers energy saving performance when the number of ONUs is either 16 or 32. Fig. 8 shows that option 3 ONU significantly outperform option 1 ONU when the TDM cycle (T_{cycle}) is less than 16ms, (i.e., $T_{\text{slot}} < 1\text{ms}$ when 16 ONUs are present and $T_{\text{slot}} < 500\mu\text{s}$ when 32 ONUs are present). The energy saving difference is more than 10% in these cases. More significantly, the result also shows that option 1 ONU fails to save any energy if the TDM time slot is less than $(N-1) \times T_{\text{slot}}$, for example an ONU cannot save energy if the overhead is longer than 342 μs when there are 16 users. This is because the overhead time exceeds the length of TDM cycle, which prevents the ONU from switching into sleep mode.

The finding is important because the sleep time for an ONU in TDM-PON is not expected to be too long when TDM traffic is involved. This is because the scheduler often grants bandwidth using just-in-time scheduling method to avoid excessive traffic backlog at either OLT or ONU. This means an ONU might need to wake up shortly after it switches to sleep mode. Furthermore, even if a round-robin type of scheduler is used, the inter-ONU scheduling cycle in TDM-PON typically

lasts only a few milliseconds to satisfy the quality of service (QoS) requirement incurred by delay sensitive applications. As a result, only the proposed option 2 and option 3 ONU could effectively reduce energy consumption using sleep mode approach under live traffic. Specifically, result from Fig. 8 show that option 3 ONU can conserve more than 50% of energy when the inter-ONU scheduling cycle is as short as 1ms.

C. Discussion

The previous analysis does not consider the traffic loss and queuing delays as a result of switching an ONU from active mode to sleep mode. If an ONU is asleep when a downstream packet arrives, the OLT would either have to queue the packet or drop it. Similarly, when new packets arrive to an ONU during its sleep mode, ONU could queue the packets before it wakes up and regain synchronization with the OLT. This process may take more than one cycle time. To resolve these problems, the OLT must adopt more advanced scheduling and protocol that would not, for example, allocate downstream packet or upstream bandwidth grants when an ONU switches to sleep mode. An example of such advanced scheduling and protocol is the energy-efficient multi-poll approach proposed in [19] for wireless local area networks. The approach in [19] has shown that effective sleep mode could be achieved with moderate buffering and enhanced scheduling of wake-up times. However, buffering increases packet delay. In TDM-PONs, the literature has also shown notable reduction of buffering delay when advanced traffic prediction models are used [20]. Although minimizing buffering delay is quite important to mitigate the effects of the sleep mode technique on traffic, the system would still certainly work without this. For instance, a simple downstream TDMA scheme that buffers excess data could certainly be used as the sleep mode scheduler.

There is also consideration to account for additional timing issues. In particular, option 1 and option 2 ONU suffers from the absence of accurate OLT clock synchronization during sleep mode. Even the frequency drift error (f_{drift}) of the ONU clock could be maintained within relative accuracy with the OLT clock frequency using self-refreshed CDR, phase errors also accumulate during sleep mode. Phase error accumulation prevents the ONU from waking up at a precise time, i.e. a free running ONU “drifts” with respect to the OLT clock. As a result, the ONU may wake up within a window of possible wake-up time, T_{drift} . The window is determined by the duration of sleep mode, T_{sleep} , and the frequency accuracy of the clock by formula (5).

$$T_{\text{drift}} = 2 * T_{\text{sleep}} * f_{\text{drift}} \quad (5)$$

Using option 2 ONU as an example, the $f_{\text{drift}} = \pm 100\text{ppm}$ and the $T_{\text{drift}} = 200\text{ns}$ if the sleep time is initially set to 1ms. Thus, additional 200ns guard time is required when the OLT wishes to schedule either downstream packets or upstream bandwidth grant to this ONU.

To summarize, a suitable high performance OLT scheduler for energy saving PON would need to consider the impact of

scheduling misses and the possibility of drifting in the wake-up time due to phase accumulation.

V. CONCLUSION

This paper presented possible implementations of sleep mode in ONUs for saving energy in PONs. Two novel ONU architectures are proposed that can significantly reduce the clock recovery overhead versus current ONU architectures when waking up from sleep mode. Analytical results show that current ONU fails to achieve an effective energy saving under realistic TDM-PON traffic. On the other hand, significant energy savings, i.e. more than 50% energy saving, are observed when using the two proposed architectures.

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