Adaptive Cyclic Transmission Operation for Energy-efficient NG-EPON

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***Abstract*—To address the growing demand of high-speed and low-latency communication in access network segment, IEEE 802.3ca task force developed Next Generation Ethernet Passive Optical Network (NG-EPON). In this network, an Optical Line Terminal (OLT) and Optical Network Unit (ONU) can have multiple transceivers which allow them to communicate through multiple channels simultaneously to achieve aggregated high transmission rate (channel bonding). Due to the use of a large number of transceivers in this network, the energy consumption should be supposedly high. In this paper, we propose an Adaptive Cyclic Transmission Operation (ACTO) scheme for NG-EPON with the objective of reducing energy consumption using sleep mode without compromising the delay performance requirements. Performance evaluated based on simulation shows that proposed solution conserves 15% of energy in ONUs even during high traffic load conditions. Furthermore, the OLT side energy consumption is also reduced by approximately 13.5% in ACTO compared to a conventional solution.**

***Index Terms*—NG-EPON, IEEE 802.3ca, sleep mode, channel bonding, cyclic transmission.**

I. INTRODUCTION

Passive Optical Networks (PONs) is a broadband access network technology that improves network access in FTTH implementations. PON technology can provide high bandwidth and low latency, thus making it a suitable choice for ever increasing user demands for connectivity. In a PON system, data is transmitted from an Optical Line Terminal (OLT) to the Optical Network Units (ONUs) which are customer premises equipment. Multiple ONUs can be associated to a single OLT. This system operates over an Optical Distribution Network (ODN) [1]. One component in the PON system is the passive splitter, located at a remote node, which guides the downstream signals to multiple ONUs connected to the OLT port [2]. This splitter is involved in combining the signal coming from multiple users in the upstream direction. Between the OLT and ONU, there are no other active components.

The ITU-T and IEEE have defined a number of architectures over the years based on PON, including Gigabit PON (GPON) and Ethernet PON (EPON) [3]. PON itself has evolved into categories based on how multiplexing is achieved, such as Time division multiplexed (TDM-PON), Wavelength division multiplexed (WDM-PON), and Hybrid (TWDM-PON) which is a combination of the previous two. IEEE 802.3ca task force introduced Next Generation EPON (NG-EPON) [4] to cope with high bandwidth demand in access network. NG-EPON uses TWDM multiplexing technique, providing an aggregated capacity of 100 *Gbps* in both direction, as depicted in Fig. 1. This is achieved by supporting up to 4 wavelengths on each fiber, each supporting 25 *Gbps*. As there are large number of transceivers are involved in an NG-EPON system to facilitate high speed communications between OLT and ONUs, the energy consumption of this network is expected to be higher relatively compare to a network like a TDM-PON if we compare both under the same number of connected ONUs. Therefore, escalating number of research efforts are noticed focusing how energy consumption in NG-EPON can be reduced using sleep mode. Although the existing solutions can potentially reduce NG-EPON energy consumption, there is still room to improve further its energy conservation performance. In this paper, we propose an Adaptive Cyclic Transmission Operation (ACTO) scheme for NG-EPON to improve its energy-efficiency. To reduce energy consumption in NG-EPON and meet traffic performance requirements, ACTO presents three key contributions: (i) it sets variable cycle duration for upstream and downstream channels taking account delay performance requirements; (ii) allows energy savings both the OLT and ONU sides by allowing their transceivers to move into sleep mode whenever possible and (iii) introduces a pair of transceivers based (one from OLT and other one from an ONU) signaling between the OLT and an ONU instead of involving their all transceivers.

The paper is organized as follows: Section II illustrates existing works in NG-EPON energy savings. The proposed solution ACTO is presented in Section III. In Section IV, we quantitatively evaluate the performance of the proposed solution. Finally, Section V concludes this work.

II. RELATED WORK

Considering NG-EPON, there have been noticeable number of works done to date on bandwidth allocation ([5], [6], [7]). Similarly to reduce energy consumption in NG-EPON, there are several works we found which we summarize in this section.

The authors in [8] studied wavelength-agile PON (WA-PON) which is a type of hybrid PON. They developed and tested a mathematical model to facilitate a transmission scheduling in WA-PON that is optimized when traffic requirements are specified. They designed Water-Filling DBWA (WF-DBWA), which is a Dynamic Bandwidth Wavelength Allocation (DBWA) scheme specifically for online operation in WA-PON. When a model for measuring energy consumption for WA-PON was developed and used, the authors found that their approach can achieve near-optimal performance when there is low traffic load. Data for average delay and packet loss ratio was also found to be optimized. In conditions where traffic load is heavy, WA-PON is able to support the requests from the subscribers. Lastly, an energy-efficient WF-DBWA scheme (EEWF-DWBA) was proposed that can conserve more energy than WF-DBWA by keeping active only the required number of wavelengths in the network. Additionally, in this solution, an ONU switches between sleep and active mode to save its energy.

In [9], energy saving was addressed in TWDM-PON based NG-EPON networks using a triple-mode approach, where a system based on the cycles was implemented along with channel tuning time and delay, while considering Quality of Service (QoS) requirements. In each cycle, Dynamic channel assignment is utilized by adopting a combinatorial optimization algorithm (Hungarian method) to save energy. The authors found that the power consumption ratio achieved the desired lowest value when the relevant tuning time cost by Hungarian assignment is used. The delay performance of the packets with high-priorities can be kept at a minimal level when the arrival time cost attribute is considered. Additionally, the study found that when the frequency of imposed channel tuning delay reduces, ONUs can move to sleep mode earlier, resulting in reduced energy consumption.

In [10], the authors proposed a transmission cycle based power conservation solution for NG-EPON. Their work identifies the idle periods in ONUs in high-load traffic environments to move them into sleep mode. The proposed scheme classifies the ONUs into intra-sleep ONU or inter-sleep ONU in each cycle. It applies intra-sleep and inter-sleep approach combined interactively for ONU based on its requested size in each cycle. In every cycle, the OLT measures the number of channels needed to serve all the ONUs. An ONU is given slots in the next channel if a given channel is already occupied. The delay performance presented based on a simulation shows that average delay of high priority downstream and upstream traffic remain within 2.5 *ms*. Later, this work was extended in [11] where the authors addressed the limitation that they found regarding the activation of the inter-cycle sleep mode, especially in medium-load environments. In this work, for an ONU to enter the inter-cycle sleep, the threshold is reduced from the previous 2 Maximum Transmission Windows (MTWs). In cases where ONUs have relatively smaller request sizes, their proposed scheme allows the ONUs to be considered to enter inter-cycle sleep mode. They found that reducing the threshold in medium-load traffic resulted in lower energy consumption of the ONU, but up to only a certain point. This limited improvement happens due to the time cycle of an EPON network which is a combination of all participating ONUs. In situations where the request size of all ONUs decreases to medium levels, the cycle time will be reduced, thereby reducing the idle period as well as their respective inter-cycle sleep time.

The authors in [12] proposed a traffic load aware TDMA mechanism that allows the OLT to grant in advance a MTW size for ONUs when traffic load goes above a threshold regardless the amount of bandwidth ONUs request. This results in a reduction of ONUs' energy consumption and eliminates the need of tuning to different wavelengths under medium to high traffic loads. The authors found that in multi-channel networks, implementing conditions before opening new channels can help reduce the number of inefficient channels. When early activation of TDMA mode is tested, for medium- to high-load environments, ONUs can maximize their sleep time and reduce their power consumption. As observed channel-saving scheme minimizes the total energy usage while impacting packet delay slightly. When early activation of TDMA mode and channels-saving are combined, this scheme has lower total power consumption, since the channel-saving scheme limits the opening of new OSUs (residing in the OLT) and its power consumption makes up a big part of total consumption. The results show that the proposed schemes improves power savings for ONU and/or OSU while also keeping the total delay at a lower level, especially for packets with high-priority.

In [13], the authors proposed to use Recurrent Neural Network (RNN) to predict the optimal sleep duration of an ONU, thereby reducing energy consumption while not compromising the required performance of traffic. The authors showed that 28% of energy saving is achieved using their proposed solution without affecting the QoS performance requirements.

III. PROPOSED ADAPTIVE CYCLIC TRANSMISSION OPERATION (ACTO)

A. *Key Concept*

In our proposed solution, both the OLT and ONUs use sleep mode to increase energy conservation. Therefore both the OLT and ONUs have sleep control unit. In the OLT side energy saving is achieved by reducing the number of active channels. Additionally, to reduce energy consumption in the active transceivers, the solution tries to identify if there is any void duration (during which there is no communication related activities) for any of the active transceivers (i.e., transmitters and receivers) in a cycle time. During such void periods, the OLT puts the transceiver into low power mode. The ONUs are equipped with multiple transceivers in the NG-EPON. The energy saving operation in the transmitters and the receivers of an ONU is managed independently. That is an ONU turns off them whenever they do not have no purpose to remain active.

The proposed ACTO determines the upstream and downstream DBA cycle length taking account Delay Requirement (DR) of each direction of traffic. In customer premises, there can be various type of applications running. Therefore, we need to schedule the traffic of different applications with non-identical DRs, including stringent and relaxed performance requirements. It is worth noting that long cycle time leads

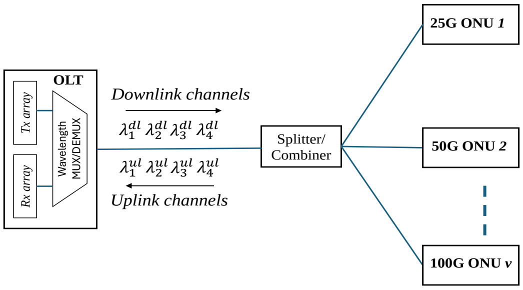

Fig. 1: A generic architecture of an NG-EPON system.

to higher delay of traffic and reduced energy consumption while reducing the number of signaling overhead in the PON system and, vice versa. However, meeting performance demand should be given more priority over energy saving and signaling overhead. Therefore, we consider adaptive cycle time for downstream and upstream channels in proposed solution. If there are K number of channels available in the PON system for downstream communications, first one (say, ch_{ω}^{dl}) or more channels are allocated for the stringent performance demanding traffic, followed by medium and low priority traffic are delivered through other channels (e.g., $ch_{\omega+1}^{dl}$ if the ch_{ω}^{dl} is already occupied). We refer ch_{ω}^{dl} and ch_{ω}^{ul} are as primary downstream and upstream channel, respectively.

Therefore, the downstream cycle time (T_c^{dl}) for the ch_{ω}^{dl} serving traffic with stringent DR is obtained as $T_{c,high}^{dl} = \min(\Phi_{dl})$ and, similarly for upstream cycle time (T_c^{ul}) for the ch_{ω}^{ul} is measured as $T_{c,high}^{ul} = \min(\Phi_{ul})$, where Φ_{dl} and Φ_{ul} is the set of DRs for different downstream and upstream traffics, respectively. Let's assume the criteria for a DR value (say, DR_j) of an application to be medium priority class is $DR_{high} > DR_j \geq DR_{low}$, where DR_{high} and DR_{low} are high and low priority DR thresholds. Then, to obtain the downstream cycle time for a channel serving medium priority class traffic ($T_{c,med}^{dl}$), we use the average value of DR_{high}^{dl} and DR_{low}^{dl}. Similarly, an upstream channel serving medium priority class traffic, we use the average of DR_{high}^{ul} and DR_{low}^{ul} to obtain its upstream cycle time. Next, for downstream and upstream low priority class traffic, we assume $T_{c,low}^{dl}$ and $T_{c,low}^{ul}$, respectively. Figure 2 shows variable cycle duration of four receivers for upstream traffic reception in an NG-EPON OLT.

1) OLT side energy saving: Assume that arrival rate for the downstream traffic and upstream traffic for v number of connected ONUs with the OLT is denoted by α_{dl}^{olt} and α_{ul}^{olt}, respectively. Therefore, the number of wavelengths (channels) required to serve the upstream traffic are presented as follows.

$$\gamma_{ul} = \begin{cases} Q+1, \text{if } \bmod\left(\frac{\lambda_{ul}^{olt} \cdot s}{T_r}\right) \neq 0 \\ Q, \qquad \text{otherwise,} \end{cases} \tag{1}$$

where Q represents quotient of $\lambda_{ul}^{olt} \cdot s$ and T_r, where λ_{ul}^{olt}, T_r and s are the upstream traffic arrival rate, upstream transmission rate of a transmitter and average frame size, respectively. Then, following a similar expression stated in (1), we obtain the required number of downstream wavelengths (γ_{dl}) at the OLT. Therefore, if the OLT has M transmitters and N receivers, the total number of active transmitters is given by $m = M - \gamma_{dl}$ and active receivers is given by $n = N - \gamma_{ul}$, respectively. In ACTO, the stringent performance demanding traffics are scheduled first in the channels and the cycle duration of the channels are determined according to the priority class. If there are empty slots in the channel during a cycle time, lower priority traffics are accommodated. The remaining low-priority traffics (if there is) is forwarded using a separate channel with different cycle time determined based on the serving priority class. However, this added channel to serve the extra traffic may not be fully utilized in cycle time. Therefore, our solution proposes to put the corresponding transmitter/receiver of such channel into low power mode within a cycle time, thereby allowing further energy saving. Note that the solution proposed in [14] puts an OLT's active transmitters and receivers into sleep mode during their idle duration. However, unlike this solution, proposed ACTO moves corresponding transmitter/receiver of the lastly added channel only during the its idle duration in a cycle time.

We now measure the average energy consumption at the OLT's receivers. Then, the energy consumption of n number receivers of the OLT during T_o is quantified as:

$$\bar{E}_{RXs}^{olt} = \sum_{i=1}^{n-1} P_{rx}^{olt,a} \cdot T_o + \frac{T_o}{T_{c(i)}^{ul}} \left\{ P_{rx}^{olt,a} \cdot \bar{T}_{rx} + P_{rx}^{olt,s} \cdot \left(T_{c(i)}^{ul} - \bar{T}_{rx} \right) \right\}, \tag{2}$$

where $\bar{T}_{rx}$ is the sum of all upstream slots in the lastly added channel, $P_{rx}^{olt,a}$ is the power consumption of OLT's receiver in active mode and $P_{rx}^{olt,s}$ is the sleep mode power consumption of the receiver of the OLT. Note that, here, when $n = 1$, the last channel is the only active one. We now measure the energy consumption of the m number of the transmitters during the T_o using a set of equations having similar form as in (3) but different parameters as follows:

$$\bar{E}_{TXs}^{olt} = \sum_{i=1}^{m-1} P_{tx}^{olt,a} \cdot T_o + \frac{T_o}{T_{c(i)}^{dl}} \left\{ P_{tx}^{olt,a} \cdot \bar{T}_{tx} + P_{rx}^{olt,s} \cdot \left(T_{c(i)}^{dl} - \bar{T}_{tx} \right) \right\}, \tag{3}$$

where $\bar{T}_{tx}$, $P_{tx}^{olt,a}$ and $P_{tx}^{olt,s}$ are the sum of all downstream slots in the lastly added channel, power consumption of a transmitter in active mode and power consumption of the transmitter at the sleep mode of the OLT, respectively. Then, total energy consumption of the OLT during T_o is measured as follows:

$$E_{OLT}^{total} = \bar{E}_{RXs}^{olt} + \bar{E}_{TXs}^{olt} + T_o \cdot P_c^{olt}, \tag{4}$$

where P_c^{olt} is the power consumption of the common components of the OLT.

2) ONU side energy saving: An ONU side energy saving is achieved by putting its transceivers into sleep mode whenever possible. In our solution, the upstream and downstream cycle times are measured for each transceiver of an ONU based on the DRs of the traffic for each direction as we discussed earlier. The duration between two consecutive slots (an upstream or a

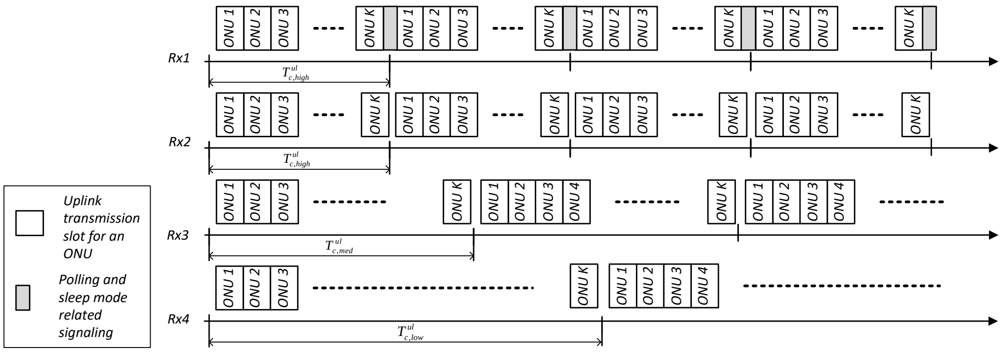

Fig. 2: Four receivers having variable cycle duration for upstream traffic reception in an OLT.

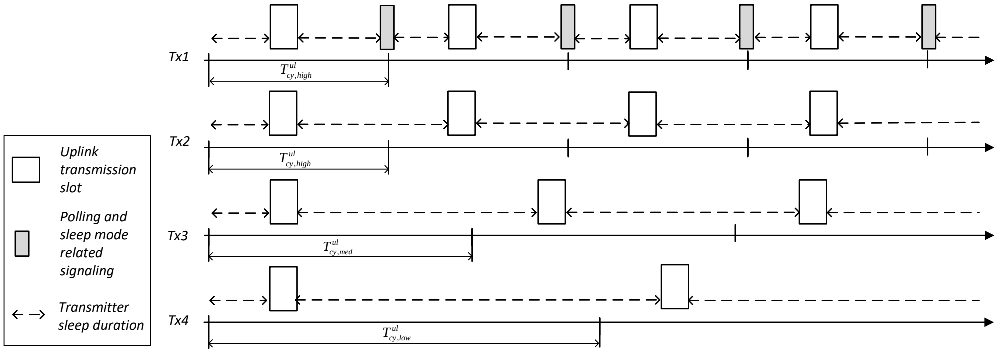

Fig. 3: Variable upstream transmission cycles for transmitters of ONU3.

downstream) is regarded as idle duration for a transmitter and a receiver of an ONU. Proposed ACTO puts the transmitter(s) and receiver(s) of an ONU in sleep mode during their idle duration, as in [10]. As an example, Fig. 3 depicts a transmission timing diagram for ONU3 having four transmitters each following non-identical upstream transmission cycle duration (the corresponding reception cycle is presented in Fig. 2). Assume *i-th* transmitter of $ONU(j)$ is polled for an upstream cycle (e.g., $T^{ul}_{c,high}$). Therefore, the sleep duration of the *i-th* transmitter of $ONU(j)$ is

$$\bar{T}^{Tx}_{s(i)} = T^{ul}_{c(i)} - t_{oh} - \left(\frac{k \cdot s}{T_r}\right), \tag{5}$$

where t_{oh}, and k are the transition overhead from sleep to active state of the *i-th* transmitter and number of transmitted frames, respectively. Assuming each transmitter is polled from different DBA cycle, the average energy consumption of the transmitters of $ONU(j)$ during a T_o period is measured as follows:

$$E_{RXs(j)} = \sum_{i=1}^{m} \frac{T_o}{T^{ul}_{c(i)}} \left\{ P^{onu,a}_{tx} \cdot \left(T^{ul}_{c(i)} - \bar{T}^{Tx}_{s(i)} \right) + P^{onu,s}_{tx} \cdot \bar{T}^{Tx}_{s(i)} \right\}, \tag{6}$$

where, $P^{onu,a}_{tx}$ and $P^{onu,s}_{tx}$ are the power consumption of the transmitter during its active and sleep periods, respectively in $ONU(j)$. As the downstream also maintains a separate transmission cycles for the receivers of the ONUs, we measure the receivers energy consumption using a similar expression as (6). Then, the overall energy consumption of $ONU(j)$ during an observation period T_{op} is as follows:

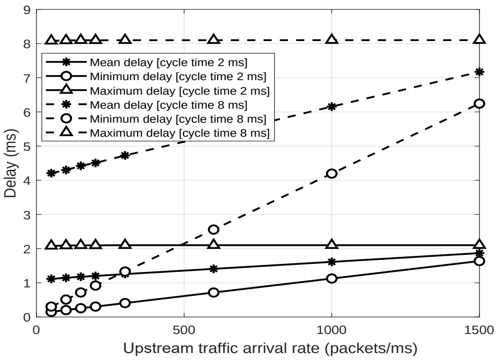

Fig. 4: Traffic delay performances under different upstream traffic arrival rates in ACTO.

$$E^{total}_{ONU(j)} = E_{RXs(j)} + E_{TXs(j)} + T_o \cdot P^{onu}_{c(j)}, \tag{7}$$

where $P^{onu}_{c(j)}$ is the power consumption of the common components of $ONU(j)$.

B. Proposed Operation Procedures

The OLT periodically observes the traffic performance requirements in each direction. It uses (1) to measure the required number of channels for both directions. Therefore, the remaining unused corresponding transceivers at the OLT

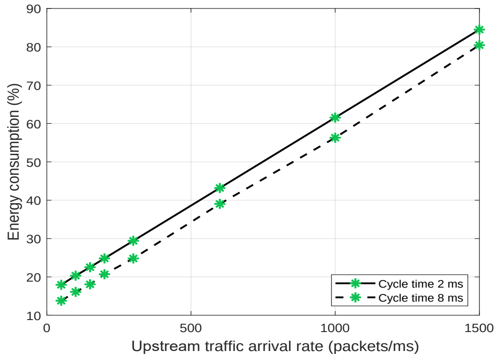

Fig. 5: ONU energy consumption for upstream traffic.

are turned off to conserve energy. The OLT also observes the traffic performance requirements and determines the optimal DBA cycle length for downstream and upstream active channels. Next, the ONUs are assigned under the active channels. In the OLT side if there's a void duration during any of the downstream and upstream transmission cycle of the lastly added channel, the OLT measures and turns off its corresponding transmitter/receiver during the idle periods to reduce further power consumption. Proposed ACTO embraces the solution proposed in [], in which the active transmitters are put into sleep mode during their unused periods. To save energy in the OLT side, ACTO relies on the conventional and the approach introduced in cite.

Inspired by the low power consuming interface based wake-up signaling mechanism for TDM-PON ONUs introduced in [15], we propose that primary upstream (ch_{ω}^{ul}) and downstream (ch_{ω}^{dl}) channels are responsible for sleep mode and bandwidth allocation related signaling in ACTO, thereby allowing the corresponding transceivers of the other channels to remain low power mode. Additionally, for example in a given situation, if the OLT observes an additional channel needs to be added into the active channel group, ch_{ω}^{ul} and ch_{ω}^{dl} can trigger an ONU to active the corresponding transmitter and/or receiver. To turn off a channel, the OLT can also use the same procedure to communicate with an ONU. Figure 3 shows an example scenario where ONU3 uses Tx1 to communicate through ch_{ω}^{ul} with the OLT for polling and sleep mode related signaling. The ONU side sleep interval for each transmitter and receiver is measured and put them into sleep mode until the next the communication related activities takes place. Conversely, the ONU transceiver associated to ch_{ω}^{ul} and ch_{ω}^{dl} channels sleep within their corresponding cycle time, as depicted in Fig. 3.

IV. PERFORMANCE EVALUATION

We narrate the performance evaluation of the proposed solution in this section. We use a discrete event simulator to evaluate the performance of proposed ACTO. The value considered for the parameters in simulation is presented in Table I.

First we evaluate the delay and energy consumption performance of the proposed solution. Figure 4 presents mean, minimum and maximum delay performances for different upstream traffic arrival at an ONU under upstream cycle duration 2 *ms* and 8 *ms*. The results show that as the traffic arrival increases, the mean, minimum and maximum delay also increases gradually under both cycle times. In particular, generally, we notice that the mean delay performance remain below the cycle duration, whereas the maximum value of delay reaches slightly above the cycle duration. This becomes more evident in the high traffic arrival regions. The factors that may have made major contribution in imposing this delay is long queuing delay when traffic arrival is high. An observation can be made from the figure is that longer cycle duration leads to higher delay performance of traffic. We can observe from Fig. 5 that the energy consumption of the ONU also gradually increases with the increase in traffic arrival (here energy consumption is presented in percentage compared with a solution that does not promote sleep mode). However, as can be noticed from this figure, a smaller cycle duration has more energy consumption compared to a larger one.

The another mechanism that contributes to yield superior outcomes of ACTO in terms of energy saving is primary upstream and downstream channel based sleep mode and bandwidth allocation related signaling (i.e., except one, other transceivers remain in sleep state until their next transmis-

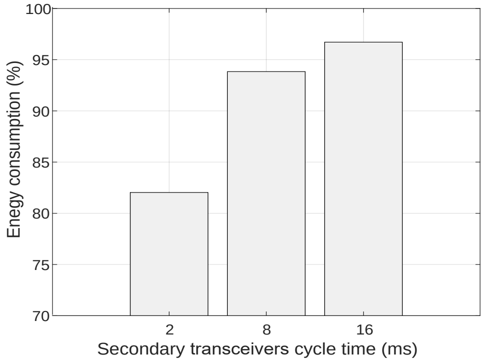

Fig. 6: Influence of primary transceiver based signaling on ONU energy conservation.

TABLE I: List of parameters considered for simulations.

Notation	Description	Value
$P_{tx}^{onu,a}$	ONU transmitter power consumption in *active state*	2.5 *W*
$P_{tx}^{onu,s}$	ONU transmitter power consumption in *sleep state*	0.25 *W*
P_{c}^{onu}	The power consumption of the common components of an ONU	3 *W*
t_{oh}	ONU transmitter/receiver transition overhead	125 μs [16]
$P_{tx}^{olt,a}$	OLT transmitter power consumption in *active state*	2.5 *W*
$P_{tx}^{olt,s}$	OLT transmitter power consumption in *sleep state*	0.25 *W*
P_{c}^{olt}	The power consumption of the common components of an OLT	5 *W*
s	Average frame size	1600 *Bytes*
T_r	Transmission rate in each direction	25 *Gbps* [6]
K	Number of channels in each direction	4 [6]

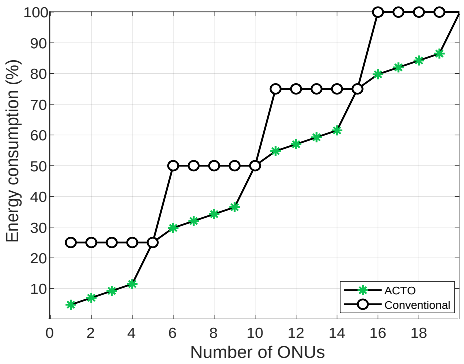

Fig. 7: OLT energy consumption performance for downstream transmission in ACTO and a conventional solution.

sion/reception slots). Here, to understand the efficacy of the proposed ACTO, we have run the simulation three times. We set the cycle time of the primary transceiver of an ONU as 2 *ms* for all three runs, however, secondary transceivers we keep cycle duration of 2 *ms*, 8 *ms* and 16 *ms* for first, second and third simulation run, respectively. Results obtained from the simulations presented in Fig. 6. Here, we compare energy consumption performance of ACTO with a solution where secondary transceivers maintain different cycle duration, however they manage polling and sleep mode related signaling independently. This figure indicates facilitating bandwidth allocation and sleep mode signaling of secondary transceivers through the primary transceiver results noticeable amount of energy savings. For example, in 2 ms and 16 ms cycle duration cases as shown in Fig. 6, ACTO yields 82% (i.e., 18% less compared to independent signaling) and 96.7% energy consumption, respectively.

Figure 7 presents energy consumption performance of an OLT in NG-EPON for downstream traffic transmission in a conventional solution and proposed ACTO. ACTO first finds the required number of channels for downstream and upstream communication based on traffic load as the same as the conventional solutions (e.g., [9]). Next, unlike the conventional solution, among the selected active transmitters and receivers, the under utilized ones in ACTO move into low power state whenever there are void slots during a cycle time to conserve energy. As we can observe from Fig. 7 that ACTO outperforms the conventional solution. However, one can notice from the figure that ACTO and conventional solution show the same performance under certain number of ONUs (under the assumption that all the ONUs have the constant bandwidth demand). Such performance can be observed during the cases when there is no underutilized downstream channels. The average energy consumption in ACTO is around 13.5% less compared to a conventional solution.

V. CONCLUSION

In this paper, we have proposed an adaptive cyclic based transmission operation in NG-EPON system. Based on simulation it has been demonstrated that proposed solution reduces energy consumption both in OLT and ONU side while showing satisfactory delay performance. This solution relies on primary channels based signaling to reduce energy consumption and number of signaling overhead. However, one potential drawback of this approach would be its inability to report the real-time bandwidth demand related information exchange for the secondary channels. In our future work, we would like to introduce Machine Learning assisted traffic demand prediction in bandwidth allocation mechanism to be overcome this limitation.

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