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Performance Analysis of TCP Traffic and Its Influence on ONU's Energy Saving in Energy Efficient TDM-PON

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Abstract

The majority of the traffic over the Internet is TCP based, which is very sensitive to packet loss and delay. Existing research efforts in TDM-Passive Optical Networks (TDM-PONs) mostly evaluate energy saving and traffic delay performances under different energy saving solutions. However, to the best of our knowledge, how energy saving mechanisms could affect TCP traffic performance in TDM-PONs has hardly been studied. In this paper, by means of our state-of-art *OPNET Modular* based TDM-PON simulator, we evaluate TCP traffic delay, throughput, and Optical Network Unit (ONU) energy consumption performances in a TDM-PON where energy saving mechanisms are employed in ONUs. Here, we study the performances under commonly used energy saving mechanisms defined in standards for TDM-PONs: cyclic sleep and doze mode. In cyclic sleep mode, we evaluate the performances under two well-known sleep interval length deciding algorithms (i.e. fixed sleep interval (FSI) and exponential sleep interval deciding (ESID)) that an OLT uses to decide sleep interval lengths for an ONU.

Findings in this paper put forward the strong relationship among TCP traffic delay, throughput and ONU energy consumption under different sleep interval lengths. Moreover, we reveal that under high TCP traffic, both FSI and ESID will end up showing similar delay, energy and throughput performance. Our findings also show that doze mode can offer better TCP throughput and delay performance at the price of consuming more energy than cyclic sleep mode. In addition, our results provide a glimpse on understanding at what point doze mode becomes futile in improving energy saving of an ONU under TCP traffic. Furthermore, in this paper, we highlight important research issues that should be studied in future research to maximize energy saving in TDM-PONs while meeting traffic Quality of Service requirements.

Keywords:
TDM-PON, Sleep Mode, Doze Mode, Energy consumption, Delay, TCP traffic performance.

1. Introduction

Maximizing energy saving in Information and Communication Technology (ICT) becomes an important goal due to rise of energy price (operation expenditure) and environmental impact. Authors in [1] forecast

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that without any improvement in power saving in technologies, the total networks power consumption in 2020 could reach up to 75% of the world electricity supply of the year 2010. Access networks consume significant portion of overall ICT energy consumption. This is principally because the access networks consist of a huge number of components (i.e. Customer Premises Equipment (CPE)).

TDM Passive Optical Networks (TDM-PONs) (e.g. Ethernet PON (EPON) and Gigabit-capable PON (GPON)) are promising access network technologies (in terms of data rate and energy consumption), and thus they have been widely deployed. Equipment of a TDM-PON are: Optical Line Terminal (OLT), Optical Network Unit (ONU), and passive splitter. In a TDM-PON, ONUs are placed at the CPE side which can support number of users; whereas, the OLT is placed at the central office of the service provider.

The operation of a TDM-PON is point-to-multipoint network in which the OLT connects multiple ONUs via optical medium through passive splitter. The OLT plays the vital role as the master device and it controls multiple slave ONUs. The main role of the OLT is to assign upstream grant time to connected ONUs to send their traffic.

An ONU in a TDM-PON sends control messages (e.g. *'Report'* control message in EPON) to the OLT mentioning its queues status. The OLT collects this information and, then uses a Dynamic Bandwidth Allocation (DBA) algorithm for calculating required upstream bandwidth for all connected ONUs. The OLT notifies the amount of allocated bandwidth to an ONU through *'Grant'* control message. The downstream traffic (from OLT to ONUs) is broadcasted to all connected ONUs. An ONU filters frames by checking frame identifier (e.g. Logical Link Identification (LLID) in EPON) of the incoming frames, and accepts frames destined to it.

Research findings reveal that access networks are the main contributor for overall ICT energy demand [2]; however, the equipment deployed in access networks are poorly utilized (findings in [3] claim that the utilization of access networks is less than 15%). This has motivated many researchers to put effort on maximizing energy saving of different access network technologies including WiMAX and Fiber-to-the-Home (FTTH).

It has been quantified in [2] that the ONUs consume 65% of the total energy consumption of a PON. Therefore, most of the energy saving research efforts are centered on maximizing energy saving at ONUs. In this perspective, researchers from academia and industry are attracted to develop and propose energy saving techniques and protocols for ONUs in TDM-PONs.

A widely used approaches to reduce an ONU's energy consumption are cyclic sleep mode and doze mode. In cyclic sleep mode, the transmitter and receiver of the fiber link in an ONU are turned *'off'* and turned *'on'* periodically. Whereas, doze mode aims to power the transmitter *'off'* in absence of upstream traffic while keeping the receiver always *'on'*. Note that there is an overhead time for ONUs to turn *'on'*/*'off'* its transceiver. The OLT uses an algorithm to decide sleep interval length. However, predicting proper sleep interval lengths is very difficult due to the bursty nature of traffic in access networks [4, 5].

The majority of Internet traffic is Transmission Control Protocol (TCP) based [6], which provides reliable connection to numerous types of Internet services, and is very sensitive to packet loss and traffic delay. Note that there is a strong trade-off relationship between delay and energy saving performance of a network. The longer a node (e.g. ONU) sleeps, the less energy it consumes, but the higher the downstream traffic delay, and vice versa [5]. In wireless networks domain, there has been many studies (e.g. [7–9]) to understand and improve TCP performance when mobile terminals use energy saving techniques (e.g. sleep mode). However, to the best of our knowledge, investigating TCP traffic performance in a TDM-PON where energy saving approaches are employed in ONUs has been barely studied.

In this paper, we evaluate TCP traffic performance under two commonly used energy saving approaches of TDM-PONs: cyclic sleep mode and doze mode. We study TCP traffic delay and throughput behavior along with energy saving performance of an ONU that adopts those energy saving approaches to maximize its energy saving. As far as we know, this is the first effort towards understanding influence of energy saving on TCP performance in TDM-PON. Here, we analyze the relation among TCP traffic delay, Throughput and ONU energy consumption. Under cyclic sleep mode, we evaluate the performance using two regularly utilized sleep interval length deciding algorithms; fixed sleep interval (FSI) and exponential sleep interval deciding (ESID). Results show that TCP throughput, delay and ONU energy performances are depended on number of TCP traffic flows. However, as the traffic increases in cyclic sleep mode, these performances can be similar for both FSI and ESID. When long sleep interval length is assigned to an ONU, it is likely to occurs OLT buffer overflow which leads to TCP downstream packet drop, chiefly under high TCP traffic flows. This consequently decreases TCP traffic throughput significantly. Moreover, in this paper, we strengthen the need for enhancing TDM-PON energy saving methods while meeting traffic Quality of Service (QoS) requirement.

The rest of the paper is organized as follows. Section 2 reviews background and related work. The system model and assumptions are described in Section 3. Section 4 presents the performance evaluation. In Section 5, we discuss and conclude our findings, and provide future direction.

2. Related Work

In this section, we introduce energy saving mechanisms recommended in the standards, popular sleep interval length deciding algorithms, and related TCP performance analysis in PONs.

2.1. Energy Saving in TDM-PONs

Early standards of TDM-PONs (e.g. IEEE 802.3ah [10]) did not consider ONUs' energy saving performance. Accordingly, an ONU transceiver remains always *'on'*. Four types of energy saving mechanisms have been recommended in ITU-T G.sup 45 [11] in order to reduce ONUs' energy consumption. These energy saving mechanisms are: cyclic sleep, doze mode, power shedding and deep sleep. Each scheme has its own energy saving strategy.

In cyclic sleep, an ONU enters into sleep state whenever there is no upstream and downstream traffic for it (cyclic sleep is known as TRx sleep in SIEPON IEEE 1904.1 [12]). Here, the OLT uses an algorithm to calculate ONU's sleep duration and notifies the ONU. Measuring a proper sleep duration is very critical in order to avoid frame delay and queue overflow at both ONU and OLT [4, 5]. When an ONU moves into sleep state, it turns *'off'* some of its energy hungry components including its transceiver. The OLT buffers all downstream traffic designated to the sleeping ONU(s) of a TDM-PON. A sleeping ONU wakes up when its allocated sleep duration expires. Additionally, a sleeping ONU needs to leave sleep state on arrival of upstream traffic from user premises, as considered in SIEPON IEEE 1904.1 [12] and ITU-T G988 [13] (this phenomenon is termed as early wake-up [12, 13]). In the doze mode, only the transmitter is turned *'off'*; so that, an ONU can save energy in absence of its upstream traffic. Note here that doze mode is equivalent to Tx sleep in SIEPON IEEE 1904.1 standard.

Shedding aims to power *'off'* or decrease the energy of unnecessary functions of an ONU while keeping the fiber link in full operation. In case of deep sleep mechanism, both the transmitter and receiver are turned *'off'* during the sleep state.

2.2. Sleep Interval Deciding Algorithms

The cyclic sleep mode is a promising approach to save energy in TDM-PON. However, the sleep interval length in cyclic sleep is very crucial and truly formidable affair since there is a significant trade-off between traffic performance and energy saving. We found in literature that the most popular algorithms in TDM-PONs for deciding sleep interval length of ONUs under cyclic sleep (TRx sleep) mode are: (1) Fixed Sleep Interval (FSI) and (2) variable sleep interval.

The FSI algorithm is widely adopted in literature (e.g. [14–17]). For instance, authors in [14] introduced a mathematical expression in order to understand energy and delay performances under FSI. In [15], authors proposed an analytical model in order to optimize the energy saving in the FSI based cyclic sleep mode. They evaluated the energy saving and delay performance varying buffer size, sleep interval length and arrival rate of an ONU. Authors concluded that buffer size must be big enough to support long sleep intervals (e.g. 50 ms).

Variable sleep interval deciding algorithms have been devised and applied in many of the sleep mode based energy saving proposals (e.g. [4, 5, 18, 19]). Exponential Sleep Interval Deciding (ESID) algorithm is the popularly used variable sleep interval length deciding algorithm. In ESID, the sleep interval length of an ONU starts from minimum sleep interval length (T_{min}) and increases up to a maximum sleep interval length

(T_{max}) as long as there is no downstream and upstream traffic for that ONU. After the end of a sleep interval, if there is no traffic, the ONU's sleep interval length increases exponentially (see Eq. 1 in Section 3.1). Authors in [5, 18, 19] used this ESID algorithm to decide length of sleep interval length of ONUs in their works.

Authors in [5] proposed an algorithm to find the lengths of T_{min} and T_{max} dynamically taking into account traffic arrival and delay requirements. Authors claimed that their proposed algorithm can meet delay requirement of traffic and save energy of ONUs noticeably. Authors in [18] found that a smaller T_{min} value in ESID algorithm leads to high energy consumption and less delay, whereas, larger T_{max} results lower energy consumption and higher delay. The authors claimed that it is important to design suitable T_{min} and T_{max} in the ESID algorithm. However, authors did not evaluate the performance of their solution under TCP traffic. Furthermore, the decision of entering into the ESID was based on downstream traffic condition.

2.3. TCP Performance Analysis

TCP performance analysis in wireless networks with energy saving techniques has been well studied (e.g. [7–9]). However, to the best of our knowledge, there is no exhaustive study that analyzes TCP performance in a PON under energy saving mechanisms.

It has to note that from literature study (e.g. [20, 21]) we can notice that there are two directions to evaluate TCP performance: (a) by taking one TCP flavor into consideration and, then looking inside the performance of TCP under different network parameters, and (b) by comparing different flavors of TCP while varying network parameters. In this paper we follow the first approach.

Early work on TCP analysis in PONs (e.g.[21–24]) revolved around mainly improving TCP performance and fairness. However, the PON architectures assumed in these research efforts did not adopt power saving mechanisms. Authors in [21, 23] proposed two polling techniques to improve TCP fairness among downstream TCP traffic. However, in their research frame loss effect on TCP performance was not considered. Authors in [24] proposed optimized pooling cycle to improve downstream TCP fairness among diversely located ONUs. Authors in [20] evaluated different TCP flavors over XG-PON with different Round Trip Time (RTT) values without taking into consideration energy saving mechanisms in PON.

We found that there is limited work in the literature concerning TCP traffic performance in an energy saving TDM-PON (e.g. [5, 25]). Authors in [5] investigated for the first time the impact of energy saving mechanism on TCP throughput. In their work, performance of TCP is evaluated under very limited condition. For instance, authors always considered fixed number of flows in their simulation environment. They presented only TCP throughput performance (TCP traffic delay behavior was not demonstrated). Consequently, it is hard to relate how TCP behaves along with energy saving mechanisms in the PONs. In [25], authors proposed a cross layer model for energy saving in the ONU. In their proposal, they analyzed TCP flows and tried to determine idle time between TCP sessions. Then, this idle time is used as sleep interval length for the ONU. The authors presented only energy saving performance of their proposal (TCP throughput and delay performance were not depicted). Our early effort to understand TCP behavior under energy saving TDM-PON presented in [26]. However, here, we presented our initial findings on TCP throughput performance under FSI algorithm.

3. Experimental Set-up and Methodology

The main objective of this paper is to investigate TCP traffic delay and throughput performances, along with ONU's energy consumption performance under two popularly used energy saving approaches: cyclic sleep mode and doze mode. In cyclic sleep mode, we use two well-known sleep interval length deciding algorithms (FSI and ESID), similar to [17].

As considered in [5, 16, 17], we assume that the OLT in a TDM-PON makes decision to put an ONU into cyclic sleep mode in absence of upstream and downstream traffic. Furthermore, we assume that the OLT invokes an ONU to enter into doze mode in absence of upstream traffic. Figure 1 shows ONU transceiver states under cyclic sleep and doze modes. As in [27, 28], we denote the case when an ONU powers *'off'* its transceiver in cyclic sleep mode as "sleep state". Whereas, in doze mode, we denote the case when the transmitter of the optical link at an ONU is powered *'off'* as "doze state". Furthermore, we denote the case when the transceiver of an ONU are powered *'on'* as "active state". We assume that under cyclic sleep mode, ONU transceiver power *'on'* overhead time is 2 ms [18, 28]. Similarly, under doze mode we assume that the transmitter power *'on'* overhead time is 2 ms [29]. We considered power *'off'* overhead time as negligible.

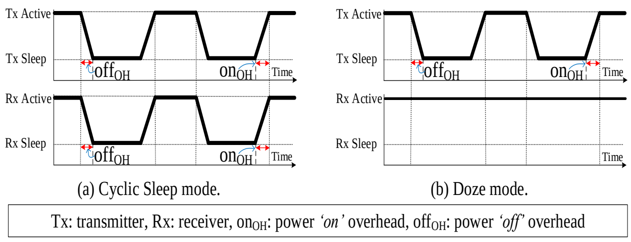


Fig. 1. ONU power levels.

Similar to [4, 5, 12], we consider that sleeping ONUs have always dedicated minimum time slot in each DBA cycle; so that, they can wake-up early without waiting for the sleep interval length to expire on arrival of upstream traffic from user premises. This allows a sleeping ONU to wake-up and send *'early-WakeUpONU'* [12] control message to claim upstream bandwidth from the OLT. Figure 2 presents the basic operation of early wake-up function, as defined in [12, 13].

In this paper, we consider that the OLT uses Interleaved Polling with Adaptive Cycle Time (IPACT) algorithm [30], which is considered as one of the best DBA algorithms specially in upstream bandwidth utilization [31].

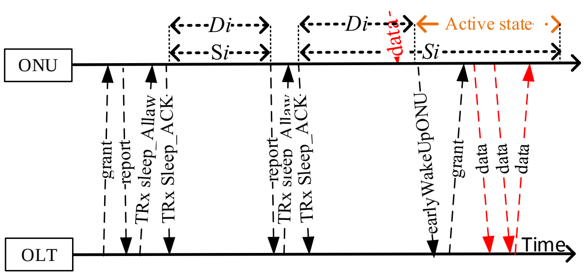


Fig. 2. Early wake-up function.

3.1. Algorithms for Deciding ONU's Sleep Interval Lengths

In this paper we compare TCP traffic and energy performance under two well known sleep interval length deciding algorithms: FSI and ESID. In FSI, sleep interval length is fixed. For instance, if the allocated sleep interval length is 5 ms for a particular ONU, the ONU should spend 5 ms in sleep state whenever it enters into this state (unless early wake-up function is executed due to arrival of upstream traffic). When the sleep interval length expires, the ONU wakes up and waits for the OLT's further instruction. In case of absence of upstream and downstream traffic, the OLT invokes the ONU to move into sleep state for another 5 ms.

As we explained earlier, in ESID, an ONU's sleep interval length is exponentially increased from T_{min} to T_{max}. The ESID algorithm is presented in Eq. 1. The OLT uses this algorithm to calculate sleep duration of an ONU. When the sleep interval length expires the ONU wakes-up and waits for the OLT's further instructions in which the OLT can assign new sleep interval length for that ONU.

$$T_j = \begin{cases} 2^{j-1} \times T_{min}, & if\ T_{min} < T_{max} \\ T_{max}, & otherwise \end{cases}, \tag{1}$$

where T_j is the duration of the *j-th* sleep interval.

3.2. Simulation Tool

To evaluate TCP performance under an energy efficient TDM-PON, we use our outstanding energy saving TDM-PON simulation model presented in [19]. This model is based on *OPNET Modular*. The network configuration for simulation is presented in Fig. 3.

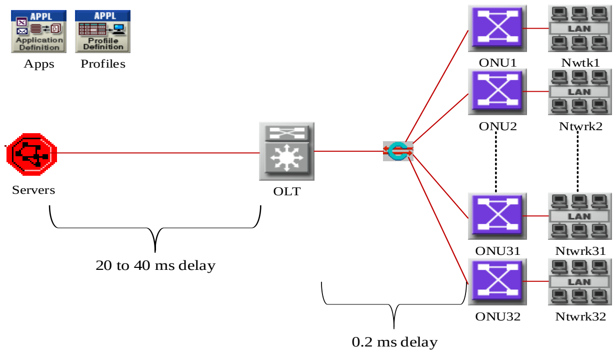


Fig. 3. Network configuration.

3.3. Traffic Profile

Similar to [7, 8], we use HTTP traffic to evaluate the performance of TCP with different sleep interval deciding algorithms. In this paper, we consider that the HTTP page inter-request time is exponentially distributed over 10 seconds. That is the default configuration for image browsing in *OPNET Modular*. We assume here that each of the TCP flows is destined to a single client connected with an ONU. To represent real network situation, in this paper, we vary the delay from a server to the OLT.

We assume that the Maximum Transfer Unit is 1500 bytes (40 bytes of TCP/IP headers and frame size is 1460 bytes). Additionally, similar to many of the existing research efforts (e.g. [7, 21]), we conduct our simulation under only TCP flows in order to ease the understanding of TCP performance results. Here, we consider that all servers adjust TCP NewReno, due to its large scale usage over the Internet [32]. Table 1 summarizes the default values of TCP NewReno, as used in *OPNET Modular*.

Table 1. TCP NewReno Parameters.

Description	Value
Maximum ACK delay	0.2 sec
Slow start initial count	2 MSS
Duplicate ACKs threshold	3
Initial Retransmission Timeout (RTO)	3 sec
Minimum RTO	1 sec

3.4. Performance Metrics

We consider mainly three performance metrics: downstream traffic delay, average throughput and ONU's energy consumption. However, when we evaluate TCP traffic performance under doze mode, we demonstrate upstream traffic delay performance instead of downstream traffic. We explain the reason in the subsequent part of this paper.

3.4.1. Downstream Frame Delay

The downstream frame delay is measured as the time difference between the time when a frame arrives at the OLT and the time when that particular frame reaches at its destination ONU.

3.4.2. Energy Consumption

In this paper we assume that an ONU can support one of two energy saving modes: cyclic sleep mode or doze mode. An ONU in an energy saving mode switches its state based on the requirement (e.g. on arrival of upstream traffic, an ONU needs to move from sleep to active state for requesting upstream bandwidth from the OLT). Table 2 summarizes simulation parameters.

Table 2. Simulation Parameters.

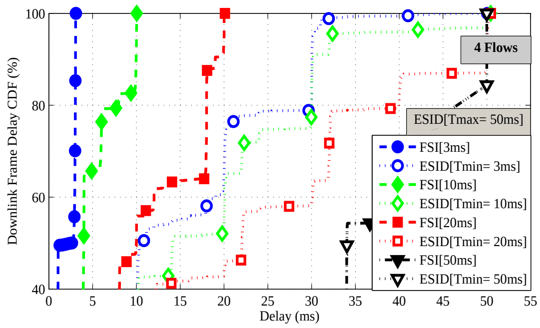
Description	Value
Power consumption in active state	4.69 W [11]
Power consumption in sleep state	0.7 W [11]
Power consumption in doze state	1.7 W [11]
Power *'on'* overhead time	2 ms [18, 28, 29]
OLT to an ONU propagation delay	0.2 ms [16]
Uplink DBA cycle	2 ms
Number of ONUs	32
OLT buffer size	32 Mb
ONU buffer size	1 Mb
Delay from the OLT to a server	20 to 40 ms
OLT-ONUs link speed	1 Gbps
OLT-servers link speed	1 Gbps

4. Performance Evaluation

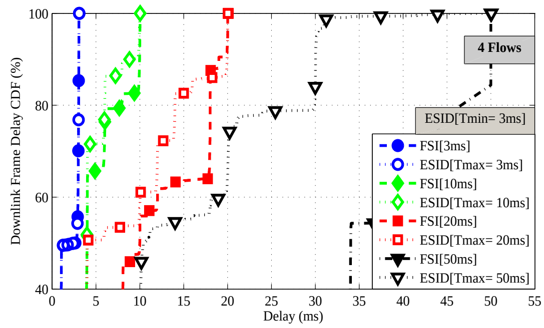
In this section, we present traffic delay, ONU's energy consumption and throughput performance. We conducted our simulation for 300 seconds. Performance results are presented for 4, 16 and 48 TCP flows. These results are obtained under the same simulation setup.

In cyclic sleep, we investigate the performance under two well-known sleep interval length deciding algorithms (i.e. FSI and ESID). In FSI, we assign different fixed sleep interval length (T_{fix}) values: 3 ms, 10 ms, 20 ms, and 50 ms. The maximum sleep interval length of an ONU is considered 50 ms [1], similar to [4, 5]. As sleep state to active state power *'on'* overhead time is 2 ms [18, 28], we assume that minimum sleep interval length of an ONU should not be less than 3 ms in order to let an ONU in sleep state at least 1 ms, as considered in [17]. In ESID, we are interested in observing the influence of different T_{min} and T_{max} on delay, throughput and energy consumption performance. Thus, the performances investigated under two assumptions; (1) we assume that T_{min} = T_{fix} (similar to [17]) and T_{max} = 50 ms, (2) we assume that T_{max} = T_{fix} and T_{min} = 3 ms. It has to note here that we denote the case when T_{min} = T_{max} = T_{fix} = 3 ms as the minimum bound of possible sleep interval length ($Bound_{min}$). Similarly, we denote the case when T_{min} = T_{max} = T_{fix} = 50 ms as the maximum bound of possible sleep interval length ($Bound_{max}$).

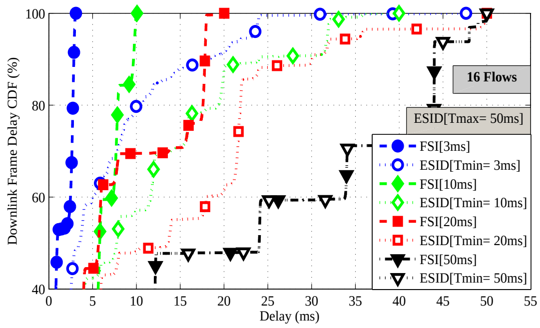
[1]In EPON, an ONU should wake-up and send *'Report'* control message to the OLT even it does not have any traffic to send and/or receive [4]. It is defined in [10, 33] that the time difference between two *'Report'* control messages should not be more than 50 ms, which enforces the ONU not to sleep more than 50 ms.



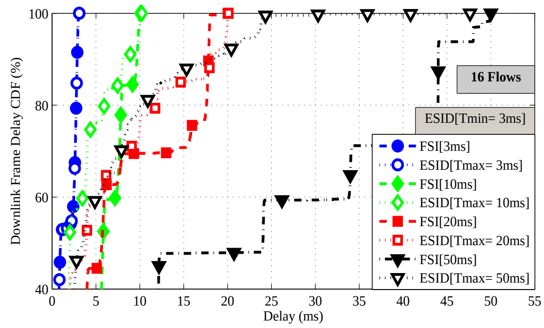
(a) Downstream frame delay under 4 TCP flows ($T_{min} = T_{fix}$).



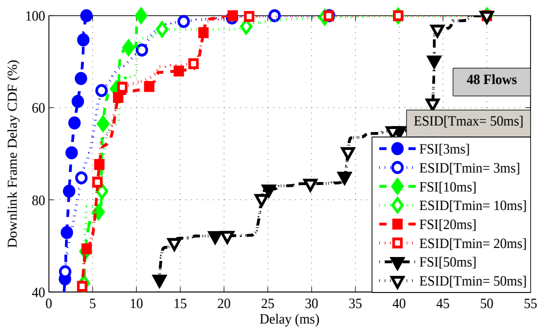
(b) Downstream frame delay under 4 TCP flows ($T_{max} = T_{fix}$).



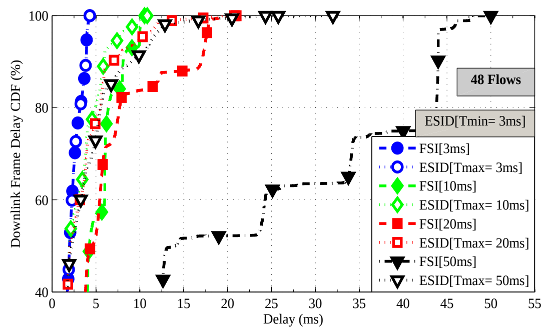
(c) Downstream frame delay under 16 TCP flows ($T_{min} = T_{fix}$).



(d) Downstream frame delay under 16 TCP flows ($T_{max} = T_{fix}$).



(e) Downstream frame delay under 48 TCP flows ($T_{min} = T_{fix}$).



(f) Downstream frame delay under 48 TCP flows ($T_{max} = T_{fix}$).

Fig. 4. Downstream frame delay performance of different flows under FSI and ESID.

4.1. Delay Performance

Depending on the sleep interval length and traffic profile, downstream traffic can experience different delay. Here, in this subsection, we investigate traffic delay performance under FSI and ESID algorithm.

To understand the aggregated results, Fig. 4(a), 4(c) and 4(e) show downstream frame delay Cumulative Distributed Function (CDF) for 4, 16 and 48 TCP flows, respectively. Here, for the ease of explanation, we assume that $T_{min} = T_{fix}$. Results show that in case of 4 TCP flows (see Fig. 4(a)), ESID and FSI algorithms are showing different delay performance for all T_{min} values except the $Bound_{max}$ case. Excluding the $Bound_{max}$ case, in all other cases, FSI is showing noticeably superior delay performance than ESID. The reason to explain this is that in 4 TCP flows case, in ESID algorithm, there will be many cases where the OLT will not have anything to forward to the ONU, and consequently, it will allow the ONU to take longer sleep causing downstream traffic to experience longer delay (in ESID, sleep interval length increases as long as there is no traffic). Conversely, under $Bound_{max}$ case, FSI and ESID are showing exactly the same performance. It is because in this particular case, ESID algorithm cannot increase sleep interval length as $T_{min} = T_{max}$. Therefore, we conclude that when $T_{min} = T_{max}$, the performances of ESID and FSI algorithms are identical under the same traffic profile.

In case of 16 TCP flows (see Fig. 4(c)), our conclusions are the same as those of the previous one (i.e. 4 TCP flows case).

Figure 4(e) presents performance results of ESID and FSI when there exists 48 TCP flows. Under such high traffic arrival scenario, an ONU barely has chance to take longer sleep. Therefore, in ESID, an ONU would have traffic to receive whenever it wakes up from sleep state. Consequently, it is very likely that an ONU's sleep interval length will never reach up to T_{max} in ESID. This results in reduction of downstream traffic delay noticeably in ESID under high traffic arrival scenarios (e.g. 48 TCP flows) compared to a low traffic arrival scenario (e.g. 4 TCP flows). We can observe that when T_{min} = 20 ms (i.e. T_{fix} = 20 ms), delay performance in both ESID and FSI are almost identical in case of 48 TCP flows. This indicates that when T_{min} = 20 ms, in ESID, almost all sleep interval lengths would be close to T_{min}, which is equal to T_{fix} as we have considered here.

Interestingly, if we compare delay performances of FSI under different TCP flows, we can notice that the traffic delay CDF results get worse as the number of TCP flows increases. If we compare the results of FSI for 4 TCP flows and 48 TCP flows presented in Fig. 4(a) and 4(e), respectively, we can notice that CDF in 4 TCP flows case is better than the 48 TCP flows case. The reason is that as the number of flows increases, delay associated with traffic processing and queuing increases.

In summary, as the number of downstream TCP flows increases, the amount of time an ONU stays in sleep state reduces, thereby improving traffic delay performance. This happens due to two reasons. First, with the rise of number of downstream flows, an ONU barely gets chance to move into sleep state. In case it gets chance to switch into sleep state, it will always have traffic to receive from the OLT after completing its first sleep interval. Under such scenario, in ESID, sleep interval length of an ONU will be always equal to T_{min}. The second reason is early wake-up of an ONU due to upstream traffic arrival. Note that TCP is a bidirectional traffic transfer-based protocol. It implies that if there is a downstream TCP flow, there will be also acknowledgment (ACK) packets on the upstream direction. With the increment of downstream TCP flows, the number of upstream ACKs increases, causing a sleeping ONU to leave sleep state (an ONU leaves sleep state earlier than an allocated sleep interval length on arrival of upstream traffic (see Fig. 2)). Therefore, we can presume that as TCP based traffic increases in the downstream, the likelihood of early wake-up increases (this may not be true when the majority of downstream traffic of a TDM-PON is User Datagram Protocol (UDP) based).

We have performed analysis to understand the influence of T_{max} on traffic delay performance in ESID algorithm. Here again, we compare ESID with FSI. For FSI, in this case, we assume that $T_{max} = T_{fix}$. Here, T_{max} is assumed to be 3 ms, 10 ms, 20 ms and 50 ms. Whereas, T_{min} is set to 3 ms. Delay performances are presented in Fig. 4(b), 4(d) and 4(f) for FSI and ESID. In case of ESID, we can observe from Fig. 4(b) that the larger the T_{max}, the worse traffic delay CDF. However, looking at Fig. 4(b), 4(d) and 4(f), we can realize that T_{max} in ESID does not significantly affect traffic delay performance as the number of TCP flows increases. The reason behind is that with high traffic arrival in ESID an ONU's sleep interval length will not have chance to reach up to T_{max} with large values (e.g. 20 ms, 40 ms, 50 ms).

4.2. ONU Energy Performance

In this part, we explain the influence of TCP traffic on energy saving performance of a TDM-PON under FSI and ESID. Similar to [5] and [3], the energy consumed by an ONU is represented as percentage of energy consumed compared to an ONU which is always *'on'* (e.g. an ONU in IEEE 802.3ah standard). We refer this type of ONU as Always *'on'* Solution (AOS).

Results in Fig. 5 show the influences of cyclic sleep mode on energy performance. Figure 5(a) represents energy performance for 4 TCP flows. We can observe that maximum energy is consumed with the smallest T_{min} in ESID (we assume here T_{fix} in FSI is equal to T_{min}). In FSI, when T_{fix} = 3 ms (see Fig. 5(a)), energy consumption reaches up to 71.1%. Whereas, in ESID, when T_{min} = 3 ms, energy consumption is only 28.2%. The reason behind is that in FSI, sleep interval length of an ONU is always fixed, forcing an ONU to wake up to check presence or absence of traffic more frequently than an ONU that uses ESID (in ESID, sleep interval length increases as long as there is no traffic for an ONU). This indicates that when number of traffic flows are small (e.g. 4 TCP flows), ESID is more energy efficient than FSI. At this point, we need to look into the delay performance CDF results once again from Fig. 4(a). We can find that with 4 TCP flows delay performance of FSI is significantly better than ESID when T_{min} = 3 ms and T_{max} = 50 ms. Therefore, we can conclude that FSI ensures better TCP delay performance compared to ESID at the price of worsening PON energy saving performance. Additionally, Fig. 5 depicts that as the length of T_{min} increases in ESID, the energy consumption performance difference under these two algorithms (FSI, ESID) gets smaller. This happens because with larger values of T_{min} in ESID, it is very likely that an ONU will have traffic to receive downstream traffic after completing its first sleep, which is equal to T_{min}. Consequently, under such scenario, an ONU will not have chance to extend its sleep interval length in ESID, and hence will end up having the same sleep interval length as an ONU with FSI algorithm.

In case of Fig. 5(c) and 5(e), our conclusions are the same as those of the figure Fig. 5. However, energy consumption performance results presented in Fig. 5(c) and 5(e) reveal that as the number of TCP flows increases, the energy consumption difference between FSI and ESID gets smaller when $T_{min} = T_{fix}$. One potential explanation for these results is that, as traffic arrival increases, ONUs under both algorithms are likely to spend the same amount of time in sleep state.

Figures 5(b), 5(d) and 5(f) represent energy consumption performance of ESID and FSI once again for 4, 16 and 48 TCP flows, respectively. At this point, we explain how energy saving performance behaves in ESID when T_{max} is varied while keeping T_{min} constant. For the ease of comparison between FSI and ESID, in FSI, we assume T_{fix} is equal to T_{max}, similar to delay performance.

From Fig. 5(b), we can notice that as the size of T_{max} increases, energy consumption of an ONU reduces in ESID. Note that Fig. 5(b) presents results for 4 flows. Under such low traffic arrival scenario, the larger the T_{max} size, the more an ONU can spend time in sleep state. In contrast to the results presented in Fig. 5(b), we can notice from Fig. 5(d) and 5(f) that the influence of T_{max} size becomes negligible with the increment of number of TCP flows (in high traffic arrival T_{max} does not affect energy saving performance as also observed in [5]). Similarly, T_{max} barely affects traffic delay performance in large number of TCP traffic flow cases, as we can notice from Fig. 4(d) and 4(f).

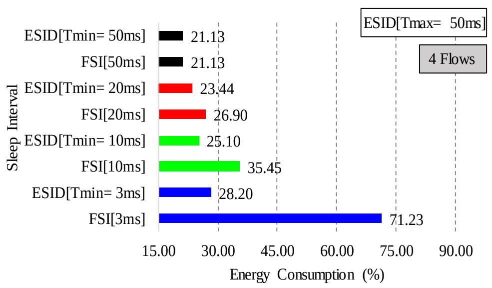
The findings from this study suggest that choosing maximum sleep interval length is very critical in energy performance in low traffic arrival scenarios.

4.3. Throughput Performance

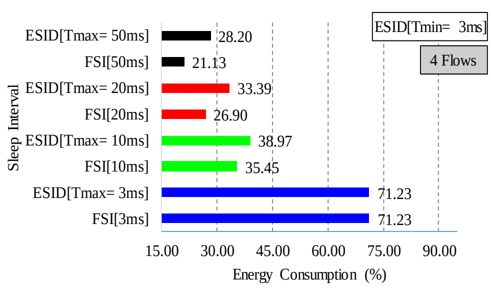
In this subsection, we present TCP throughput performance under FSI and ESID algorithms. As we did in the previous performance results, here, we present throughput performance for different T_{min} and T_{max} under ESID algorithm. We also demonstrate results for different T_{fix} values in FSI algorithm. Besides, we demonstrate TCP throughput performance for AOS solution.

Under low traffic profile (i.e. 4 TCP flows) the ONU's sleep interval length can reach up to the T_{max} in case of ESID as we have explained earlier. Furthermore, it can stay in sleep state with a little interruption from early wake-up function. These contribute in increasing traffic delay (results presented in subsection 4.1 explain the strong positive correlation between sleep interval length and traffic delay increment). Indeed, long RTT and packet drop can significantly influence the throughput of TCP flows [5, 20]. Note that delay due to sleep mode can influence in increasing RTT value between a TCP server and a client, thus resulting in declining TCP throughput performance.

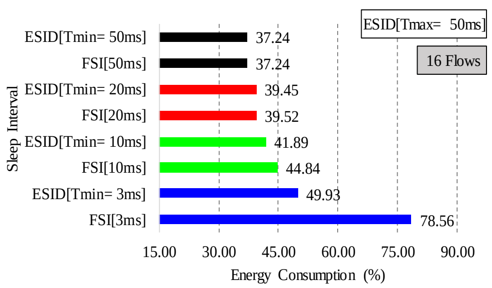
Findings in Fig. 6 show that under different TCP traffic flows even with the $Bound_{min}$ case the throughput performance is degraded perceivably compared to throughput performance of AOS. On the other hand, we can notice from this figure that we can get the worst TCP throughput results among all in $Bound_{max}$ case. In that particular case, delay performance is also the worst among all other results if we observe Fig. 4. This finding confirms the strong association between downstream traffic delay performance and throughput results.



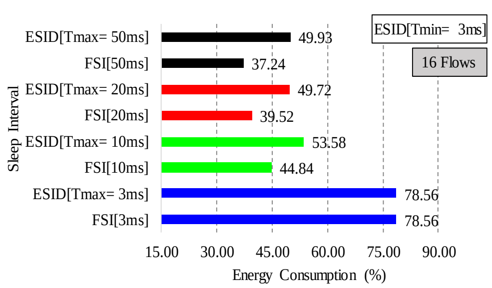
(a) Energy consumption under 4 TCP flows ($T_{min} = T_{fix}$).



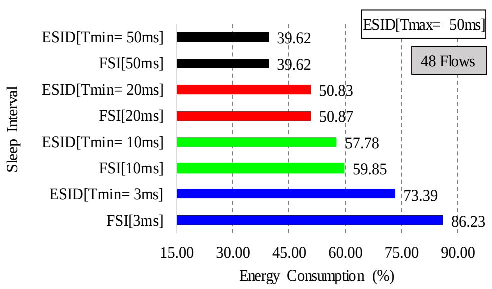
(b) Energy consumption under 4 TCP flows ($T_{max} = T_{fix}$).



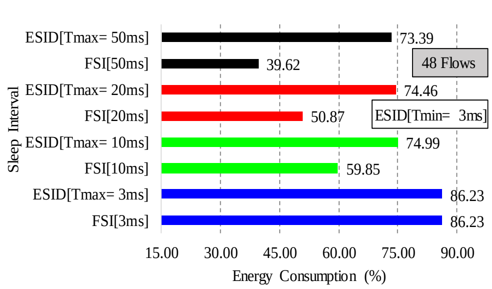
(c) Energy consumption under 16 TCP flows ($T_{min} = T_{fix}$).



(d) Energy consumption under 16 TCP flows ($T_{max} = T_{fix}$).



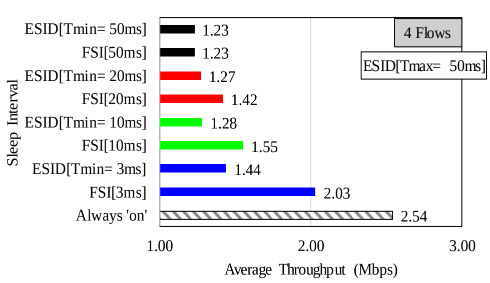
(e) Energy consumption under 48 TCP flows ($T_{min} = T_{fix}$).



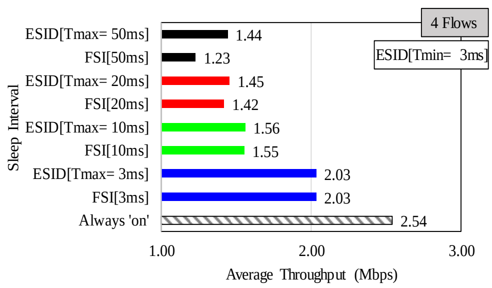
(f) Energy consumption under 48 TCP flows ($T_{max} = T_{fix}$).

Fig. 5. ONU relative energy consumption performance under different flows.

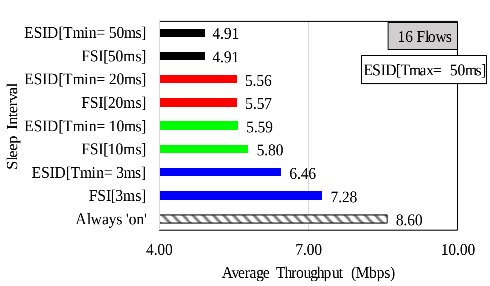
Looking into Fig. 6(a), 6(c) and 6(e), we can notice that the larger the size of T_{min} in ESID, the poorer the throughput performance. This statement is also true for FSI algorithm, as we can observe from those figures. Although we consider $T_{min} = T_{fix}$ in our performance evaluation, we can notice from Fig. 6(a) that under 4 flows, FSI is showing superior performance than ESID. Note that when there exists only 4 flows, an ONU in ESID can extend sleep interval length in absence of traffic (sleep interval length could reach up to T_{max}). Consequently, when downstream traffic arrives for a sleeping ONU at the OLT, those traffic could experience very long delay in ESID compared to FSI where an ONU always uses a fixed sleep interval length (see Fig. 4(a)). We can notice from Fig. 4(a), 4(c) and 4(e) that traffic delay performance difference under FSI and ESID gets smaller as the number of traffic flows increases. Similarly, from Fig. 6(a), 6(c) and 6(e), we can notice that FSI and ESID can provide almost the same throughput performance as the number



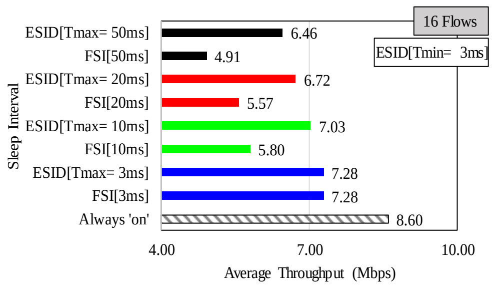
(a) Throughput under 4 TCP flows ($T_{min} = T_{fix}$).



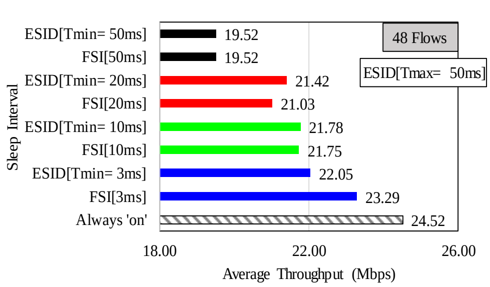
(b) Throughput under 4 TCP flows ($T_{max} = T_{fix}$).



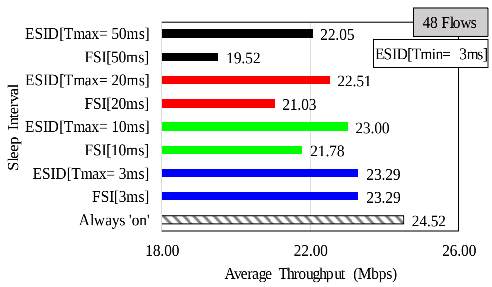
(c) Throughput under 16 TCP flows ($T_{min} = T_{fix}$).



(d) Throughput under 16 TCP flows ($T_{max} = T_{fix}$).



(e) Throughput under 48 TCP flows ($T_{min} = T_{fix}$).



(f) Throughput under 48 TCP flows ($T_{max} = T_{fix}$).

Fig. 6. Average throughput performance of different flows under FSI and ESID.

of TCP flows increases. Therefore, we can conclude that under high traffic arrival rate scenarios (e.g. 48 flow), both FSI and ESID will end up showing almost the same throughput, energy and delay performance.

Figure 6(e) shows that we can obtain the worst average throughput performance in $Bound_{max}$. After observing simulation data, we have pointed out two important factors accounting for TCP throughput degradation when these algorithms use $Bound_{max}$. First, long sleep interval length (e.g. 50 ms) imposes long RTT, which in turn reduces TCP throughput performance. Second, long sleep duration of ONUs forces the OLT to buffer all the packets of sleeping ONUs for long period of time resulting buffer overflow, thus reducing throughput performance of TCP. Note here, 48 flows with $Bound_{max}$ is the only case where we observe packet drop from our simulator trace results.

For understanding packet drop behavior under $Bound_{max}$, we increase the number of downstream flows in our simulation up to 216 flows. Packet drop ratio under different number of TCP flows is presented in Fig. 7. Results show that with 48 TCP flows the packet drop ratio at the OLT under $Bound_{max}$ is below 0.5%. However, as the number of flows increases, the packet drop also increases noticeably up to 96 flows. Interestingly, after 96 flows, packet drop ratio falls pointedly and at 120 flows the packet drop ratio is 0%. Then again, after 144 flows, a slow upward trend of packet drop is observed from the figure. Therefore, we can observe packet drop in two regions: between 48 flows and 120 flows, and after 144 flows. In fact, the reason behind packet drop when the number of flows is between 48 and 120 is ONU sleep mode. Under this high traffic arrival scenario, whenever an ONU moves into sleep state, the OLT's buffer overflow. However, after a certain number of flows, the ONU does not have chance to move into sleep state anymore, causing reduction in packet drop at the OLT (at this point the OLT does not need to buffer any packet for the ONU (no packet drop is observed between 120 flows and 144 flows)). However, with the increment of the TCP flows (after 144 flows), we can notice packet drop again due to ONU's downstream bandwidth saturation (available bandwidth is insufficient to handle the downstream traffic load).

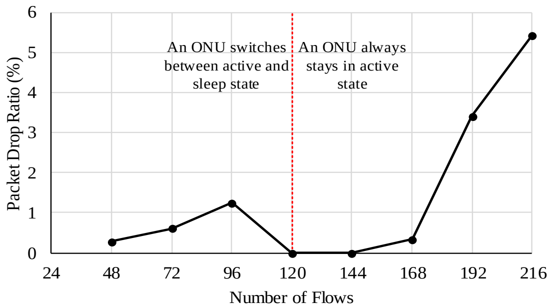


Fig. 7. Packet drop ratio under $Bound_{max}$.

At this point, we are interested to see the influence of T_{max} in ESID and T_{fix} in FSI on TCP throughput performance. Here, we set $T_{max} = T_{fix}$, and keep $T_{min} = 3$ ms in ESID. Looking into Fig. 6(b), we can observe that the longer T_{fix} in FSI and T_{max} in ESID the lower the throughput we can gain (we can notice the same behavior from 6(d) and 6(f) for 16 and 48 flows, respectively). Interestingly, similar to the delay and energy consumption results presented in Fig. 4 and Fig. 5, respectively, we can notice from Fig. 6(b), 6(d) and 6(f) that as the number of TCP flows increases, the influence of T_{max} on throughput performance in ESID gets negligible.

4.4. Performance in Doze Mode

Here, we are interested in studying the influence of ONU doze mode on TCP traffic performance. In this subsection, aside from demonstrating TCP throughput and delay performance, we provide an ONU's energy consumption performance when doze mode is in use. Note that in doze mode, an ONU keeps its receiver active always regardless the presence or absence of traffic [11, 12]. Therefore, unlike the cyclic sleep mode case in which the OLT needs to buffer traffic for a sleeping ONU, the OLT can forward traffic directly to the ONU when an ONU uses doze mode. As a result, in doze mode case, downstream frame delay performance is the same as in the AOS case. Hence, here, we evaluate only upstream traffic delay performance for AOS and doze mode under 4, 16 and 48 TCP flows.

Results in Fig. 8 show the upstream delay performance in doze mode and AOS. The AOS results show that as number of flows increases some packets can experience delay beyond one DBA cycle (in our simulation, we consider DBA cycle length is 2 ms). This phenomenon has been revealed in [30]. Looking into the results of doze mode, we can observe that delay performance under doze mode is worse than AOS. This is due to the additional transition overhead time (i.e. 2 ms [29]) required for an ONU in doze mode to move from doze state to active state on arrival of upstream traffic. As we can notice from Fig. 9(a)

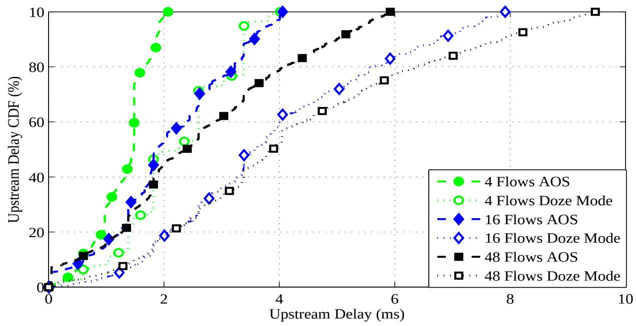
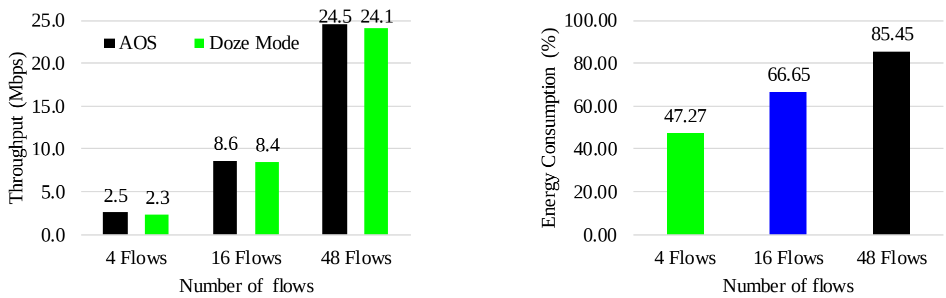


Fig. 8. Upstream delay under doze mode.



(a) Average throughput.

(b) Energy consumption.

Fig. 9. Throughput and energy performance results under doze mode.

that the average throughput (comparing AOS and doze mode) is almost similar. Whereas, as we notice the energy saving performance of doze mode, we can observe that with low traffic flows, an ONU can save significant amount of energy (in case of 4 flows, doze mode consumes around 47% of AOS (see Fig. 9(b)). However, results show that energy consumption significantly rises as the number of flows increases (see results of 48 flows in Fig. 9(b)). It is because, with the increment of downstream TCP flows, the number of upstream TCP ACK packets increases, thereby forcing the transmitter of an ONU to be active for long duration for serving upstream packets. Therefore, we conclude that with large number of TCP flows, energy consumption performance under doze mode and AOS will be almost the same.

5. Conclusion and Discussion for Future Research

We have analyzed TCP traffic performance in TDM-PON under two widely used energy saving modes (cyclic sleep and doze mode). Specifically, we have investigated the performance of delay and throughput for different number of TCP flows. Furthermore, we have analyzed ONU energy consumption performance. When we evaluated the performances in cyclic sleep mode, we have presented results for two well-known sleep interval length deciding algorithms (FSI, ESID) that an OLT uses to decide sleep interval lengths for an ONU. It must be noted that this paper is the first effort dedicated towards understanding TCP traffic performance in an energy saving TDM-PON.

Under cyclic sleep mode, we have confirmed the strong relationship between downstream traffic delay performance, ONU's energy consumption and throughput results. Moreover, we reveal that under high traffic arrival rate scenarios (e.g. 48 flows), both FSI and ESID will end up showing almost the same throughput, energy and delay performance. Furthermore, long sleep interval length (e.g. 50 ms) could increase RTT and packet drop, which in turn reduces TCP throughput performance. In case of doze mode, we noticed that TCP throughput is very close to the throughput results of AOS. Under low traffic load scenarios, doze mode saves energy significantly. However, at high traffic arrival scenarios, energy consumption performance of doze mode and AOS would be almost identical.

In the following paragraphs, based on our study, we point out few important research issues that should be addressed in future in oder to maximize energy saving performance of TDM-PONs while meeting TCP throughput and delay performance requirements.

In the Internet there are various TCP flavors (in this study, we used TCP NewReno). It is important to examine the performance of TCP variant under energy efficient PON. In this paper, we have noticed that due to the sleep mode, RTT of TCP flows can be increased which in turn could reduce TCP throughput. Increasing the number of competing TCP flows could also affect the fairness among flows when sleep mode is implemented, as authors in [9] noted based on their findings in wireless access network domain. We believe that investigating the fairness between competing TCP flows in an energy efficient PON can make better understanding in developing new TCP congestion control, DBA and sleep interval deciding algorithms in order to meet PON traffic requirements while saving energy in TDM-PONs as much as possible.

We reveal that doze mode has significant improvement on TCP throughput performance. However, it shows that energy saving performance degrades dramatically as the amount TCP traffic increases. The conventional ONU architecture fails to properly utilize doze mode due to its long transition overhead time from doze to active state. Similarly, in cyclic sleep mode, an ONU needs around 2 ms to transit from sleep to active state, thereby deteriorating energy saving performance of ONUs. To maximize energy saving performance in power saving modes, research effort is needed to reduce transition overhead time.

Early wake-up function triggering conditions are not in the scope of the standards (i.e. [12], [13]). The early wake-up function of an ONU can interrupt and force the ONU to leave sleep state prior to its allocated sleep interval length. This leads to increase in energy consumption of ONUs.

Acknowledgment

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