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Sleep assistive dynamic bandwidth assignment scheme for passive optical network (PON)

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Abstract

In passive optical network (PON), in addition to efficient bandwidth management, a dynamic bandwidth assignment (DBA) scheme can also enhance the energy efficiency performance of the optical networks units (ONUs) during sleep mode. A few such green DBA schemes have been proposed in literature for EPON, however, ITU compliant PONs have not got attention. In this study, the role of a DBA scheme during the cyclic sleep mode for XGPON has been investigated. A sleep assistive (SA)-DBA scheme is proposed that not only improves the energy saving performance of cyclic sleep mode but also reduces the upstream delays and variance for all the type-2 (T2), type-3 (T3) and type-4 (T4) traffic classes. Although, the upstream delay of type-1 (T1) traffic class slightly increases, the average upstream delay of all the traffic classes remains below the set target delay limit of 56 ms.

Keywords Bandwidth efficient · Bandwidth assignment · Energy efficient · PON · XGPON

1 Introduction

TODAY is the era of Information and Communication Technology (ICT). According to the latest report of the International Telecommunication Union (ITU) [1], 53.6% of the world population has got an Internet connection at their homes. In developed countries, this ratio is even higher and 84.4% of the population has access to the Internet. Due to this widespread Internet use, the demand for the high-speed broadband services is continuously increasing and a rise of 30% in broadband subscriptions has been recorded in the last 5 years [1]. For the delivery of broadband services to customers, passive optical network (PON) has emerged as the most suitable optical fiber based Access Network which offers up to 40 Gbps line rates [2].

This massive expansion of ICT networks has also increased the power generation requirements of this sector [3]. Since, still today, most of the power generation plants are thermal that require burning of fossil fuel resources like coal, oil, and gas [4], therefore, the carbon footprint of the ICT sector has also increased and has been estimated to be 2.5%. Specifically, the Telecom sector is responsible for 22% of the greenhouse gas (GHG) emissions [5] and it is expected that this situation will aggravate further in future [6]. Therefore, the energy efficiency of the ICT sector is important and many studies have addressed this problem and it is still an active research area.

Most of the power consumption in the Telecom sector is in the Access Network which is responsible for 70% of the power consumption. The evolution of Access Network toward PON has significantly reduced this power consumption due to its passive nature and longer reach. The longer reach not only reduces the power consumption of the access loop but also reduces the maintenance costs due to the lesser number of central offices compared to copper and active optical networks [7, 8]. However, in PON, the main problem lies in the optical network units (ONUs) which consume 60% of the PON power.

The main cause of high power consumption of ONU is broadcast and select mechanism in the downstream (DS) direction in all of the present PON technologies like GPON,

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EPON and near future PON technologies; XGPON, 10G EPON and TWDM PON [9]. This is because a group of ONUs receive the DS frames on the same wavelength and are forced to remain in the active state to receive each DS frame, process it completely and then discard up to 97–99% of it for not being relevant. To conserve ONU energy, ONU sleep mode has been widely used to switch ONU to low power mode when it is idle or its traffic load is very low. Specifically, cyclic sleep mode (CSM) has been successfully shown to save up to 85% of the ONU power [10]. Some of the sleep mode schemes like [11, 12] require newer ONU architecture but the biggest advantage of CSM is that it does not require any architectural changes or any new investment. Moreover, it has been adapted by both IEEE and ITU as standard energy conservation scheme for their respective PON standards.

However, all of the PON technologies described above require bandwidth management mechanism as in the upstream (US) direction as all the ONUs cannot simultaneously transmit to OLT at the same wavelength as this will cause a signal collision. Therefore, for the US link, a dynamic bandwidth assignment (DBA) scheme is used as a static bandwidth assignment (SBA) scheme is neither bandwidth efficient and nor it can assign bandwidth to multiple traffic classes of an ONU. Thus, the US delay performance of all the ITU defined traffic classes; type-2 (T2), type-3 (T3) and type-4 (T4) for PON and IETF DiffServ classes; assured forward (AF), expedited forward (EF) and best effort (BE) used by EPON/10G EPON studies is critically dependant on DBA performance. Generally, in a sleep mode scheme, there is a trade-off between the energy savings and the US and DS communication delays [13]. However, the role of a DBA is also very important as any degradation in DBA performance will also affect the sleep mode performance.

Many, energy efficient DBA schemes for EPON have been proposed [14, 15] that use the DBA process to control the sleep mode process. However, these schemes require faster ONU architecture and cannot work with current ONUs. To the best of our knowledge, all of the current sleep studies, especially for ITU compliant PONs (GPON, XGPON and TWDM PON) either assume a SBA [16, 17] or do not consider the impact of the DBA scheme by assuming it to be perfectly working [18] during sleep studies except our earlier CSM study in [10].

In this study, we have investigated the impact of DBA performance on CSM and used the immediate allocation with colorless grant (IACG) DBA scheme for the performance study of the energy efficient cyclic sleep control (ECS) framework. We have presented a sleep assistive (SA) DBA scheme and show that compared to IACG, it not only increases the overall ONU energy savings but also reduces the US delays and variance of T2, T3 and T4 traffic classes as well as guarantees adherence to average delay limit of 56 ms delay limit for both US and DS traffic using the sleep buffer approach [10]. To assist CSM, a slight modification is also proposed in standard CSM process of the ONU. Table 1 shows all the important acronyms and notations used in rest of the paper.

Table 1 Table of important acronyms and symbols

Parameter	Details
BWmap	A field in DS XGPON frame that carries US bandwidth assignments for each ONU traffic class
RBW	Remainder unassigned bandwidth
GPA	Guaranteed phase allocation
SPA	Surplus phase allocation
BM-CDR	Burst mode clock and data recovery
CM-CDR	Continuous mode clock and data recovery.
AS	Asleep
SLA	Sleep aware
AF	Active free
AH	Active held
ALS	Alerted sleep
BW_{ONU}	The ONU to OLT line rate
$D_{\mathrm{US}}/D_{\mathrm{DS}}$	The target average delay limits for upstream and downstream traffic
T_{AS}	ONU asleep state time
T_{AWARE}	ONU sleep aware state time
T_{ERI}	OLT CSM timer. Refer Fig. 3
T_{Alerted}	OLT CSM timer. Refer Fig. 3
T_{Hold}	ONU timer for stay in active Held state
BW_{ONU}	ONU to OLT Line rate

The rest of the paper is organized as follows: Sect. 2 reviews the related work, Sect. 3 explains the ECS framework, Sect. 4 describes sleep assistive (SA)-DBA scheme, Sect. 5 describes the simulation setup, Sect. 6 presents and discusses the results. Finally, Sect. 7 concludes this paper and with future research direction.

2 Related work

The DBA schemes for PON can be broadly classified as traffic monitoring (TM) based or status reporting (SR) based. The TM approach is used by the ONUs with limited memory. In this approach OLT estimates, the ONU traffic demand from its traffic arrival rate and assigns bandwidth accordingly [19–21]. Most of the DBA schemes are SR based in which all the ONUs maintain a traffic queue for each supported traffic class and periodically inform OLT about the queue length information using the US messaging channel. Based on the particular DBA scheme and the received queue reports, the OLT assigns bandwidth to each ONU using the BWmap field of DS frame, in case of ITU PONs, or the MPCP GATE message, in case of IEEE PONs. Broadly, IEEE PON DBA schemes can be classified as single thread (ST) [22] and multi-thread (MT) [23]. The ST schemes only execute a single DBA process for each ONU, while the MT schemes execute multiple DBA processes simultaneously for each ONU. These schemes can be executed with an online, offline or an online–offline hybrid manner. In the first case, OLT assigns bandwidth to an ONU as soon as it receives the queue report from it, while in the second case OLT waits for all the queue reports and in the last case, it only waits for a group of ONUs. Unlike, IEEE PONs, the ITU PONs are synchronous in which all the ONUs can send queue report to the OLT in the single US frame and be assigned bandwidth accordingly in a single DS frame; therefore, there is no online or offline differentiation. However, they can be classified as fixed SI based c or flexible service interval based [24]. In both cases, the bandwidth assignment cycle comprises of a GPA in which a minimum bandwidth is assigned according to the service level agreement and an SPA in which surplus bandwidth is assigned as per the agreed service level agreement. In addition to these phases, the DBA schemes in [25] also assign the RBW to ONUs to further improve the US performance. A few DBA schemes also utilize the remaining unused bandwidth (UBW) of the lightly loaded ONU queues and assign it to the heavily loaded queues of the same traffic class in other ONUs [25, 26]. However, all of above discussed DBA schemes assume an ONU to be always in active state and do not consider the ONU low power mode. A recent detailed review of all such DBA schemes is given in [27].

However, there are many DBA schemes that have considered the integration of DBA and sleep mode schemes. These schemes execute the DBA process in parallel to sleep process and make an ONU switch to AS state, if idle, during a DBA cycle [28] to conserve energy. Some schemes compute the DBA cycle by only considering the US traffic termed as upstream centric (UCS) like ALS [11] and GBA [12]. These schemes provide very high energy savings but suffer from higher DS delays and are improved by the downstream centric approach (DCS) in which both US and DS traffic is considered for the US time slot allocations. The SDBA [29] follows this approach and assigns equal US time slot to ONUs keeping in view the target average delays and frame loss rates of both US and DS traffic. The ONU sends the estimated US traffic rates to OLT through the modified MPCP REPORT message. The DS transmissions are locked to the same US slot. If the ONUs have low traffic load, they switch to sleep state and if completely idle then they may be allowed to sleep in contiguous US slots to conserve energy. A further improvement in SDBA is EDBA which also offers an additional provision of Doze mode to an ONU. An ONU can switch to Doze mode if there is DS traffic being received by it but no US traffic is available to send to OLT. A similar proposal in [30, 31] presents a modified IPACT scheme to support sleep mode termed as sleep mode aware (SMA) algorithm. The ONU is only active during the transmission time slot (TS) and during a DBA cycle but in AS state otherwise. This TS is computed keeping in view both US and DS traffic queues and is selected as the time required to clear off the minimum (of US and DS) backlog traffic. If the TS is longer and ONU do not have traffic to transmit US, it goes to doze mode for the remaining time. The OLT assigns the TS and the next wakeup time for sending the Gate message from OLT via REPORT message to ONU. However, OLT does not know the time of next GATE message and predicts it based on the current transmission time of the other ONUs. This prediction may fail due to bursty nature of traffic and may lead to severe US performance degradation. The study in [32] improves SDBA by assigning unequal time slots to ONUs. The lightly loaded ONUs are assigned equal bandwidth according to their SLA but the heavily loaded ONUs are assigned the available excess bandwidth equally. For improving the energy efficiency, this scheme optimizes the ONU polling order during a DBA cycle to reduce the ONU Active state time. The results show higher energy savings compared to UCS approach. The study in [33] presents an upstream DBA (UDBA) scheme in which OLT has a dedicated unit at the OLT for deciding the ONU Active, Doze, Sleep or Transmission mode based on the information of the US and DS traffic information. The study in [34] suggests the use of vertical cavity laser (VCSEL) instead of normally used DFB lasers helps to significantly enhance the energy efficiency of the DBA scheme by reducing the transition time and power consumption of ONU AS state to Active vice versa.

However, most of UCS- and DCS-based schemes require some physical layer changes in the ONU like BM-CDR instead of CM-CDR [35]. Moreover, these schemes have been presented and tested with IEEE compliant PONs. The ITU compliant PONs have significant MAC layer differences, thus, their DBA process. For ITU compliant PONs, a DBA scheme that can work with CSM is more feasible as it is a standard energy conservation scheme for these PONs. To the best of our knowledge, no such DBA scheme for ITU compliant PONs has been proposed. The DBA scheme presented in our earlier work in [36] improved the scheduling mechanism to improve bandwidth assignment to higher priority traffic classes. An updated version presented in [37] also improved the performance of lower priority traffic classes by utilizing the used bandwidth of the ONUs for XGPON and for LR-PON in [26]. However, none of these schemes considered the energy saving mode of the ONUs. Therefore, this study presents an improved DBA scheme that assists the CSM process and helps an ONU to prolong it's AS state and, thus, improve its energy saving performance due to least power consumption of ONU in AS state.

3 Energy efficient CSM framework

The performance of the CSM process depends on the optimized configuration of T_{AS}, LWI events and various ONU and OLT timers. This study uses the energy efficient CSM (ECSM) framework, presented in our earlier work in [38], to optimally configure the CSM process according to the target US and DS delay limits; D_{US} and D_{DS}. The ECSM scheme follows a sleep buffer approach to optimize the performance of the CSM process. An ONU entering the AS state quits it when any of the US or DS buffer is full due to triggering of the respective LWI event. All the optimal values for the ONU US and DS sleep buffers and other CSM control parameters and timers are computed using ECSM framework so as to maximize the ONU energy savings while still adhering to target average delay limits. To ease the CSM configuration, a comprehensive algorithm (Algorithm 1) is presented in this study that summarizes the working of ECSM framework and shows the step-by-step computation of all the CSM parameters and timers. This algorithm can be used by a PON operator to configure the CSM process for both the OLT and the ONUs according to the desired target US and DS arrival rates; $\lambda_{\mathrm{US\_T}}$ and $\lambda_{\mathrm{DS\_T}}$ according to its agreed data rates for a user group as per its SLA. Here for simplicity it is assumed that all the ONUs have same SLA. In the first step, the algorithm computes the required US and DS sleep buffer sizes N_{US} and N_{DS} at the ONUs and the OLT. These additional memory buffers will be required to store the traffic arrivals during the AS state of the ONU. Where the T_{init} is the wakeup time required by ONU to transition from AS state to Active state and SI is the time period after which the OLT computes the dynamic bandwidth assignment (DBA) process according to newly received queue reports from the ONUs. Since the US service rates for T1, T2, T3 and T4 traffic classes are different due to different bandwidth guarantees as per SLA. Therefore, in step 2, the N_{US} is divided to N_{US1}, N_{US2} and N_{US3} in proportion of the maximum guaranteed bandwidths $\mathrm{AB}_{\mathrm{min1}}$ and $\mathrm{AB}_{\mathrm{min2}}$ to T1 and T2 traffic classes and to T3 in proportion to the sum of maximum guaranteed ($\mathrm{AB}_{\mathrm{min3}}$) and surplus bandwidths ($\mathrm{AB}_{\mathrm{sur3}}$). Since T4 works on best effort basis, it is only allowed a maximum surplus bandwidth $\mathrm{AB}_{\mathrm{sur4}}$. Thus, the T4 traffic class will only get US bandwidth allocations if the maximum load is less than system capacity. Thus, N_{US4} is assigned in proportion to the difference of the maximum expected load per ONU and $\mathrm{BW}_{\mathrm{ONU}}$. The ECSM scheme allows an ONU to remain in AS state unless any of the US or DS buffer is full which leads to the triggering of LWI event at the OLT or ONU. Thus, at low traffic rates an ONU remains in AS state for longer time due to slow filling of the US and DS sleep buffers.

Algorithm 1: *Algorithm to configure Cyclic Sleep Mode for ITU PONs according to sleep buffer approach.*

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Input: Target US and DS average delay limits $D_{US}$ and $D_{DS}$ and the target traffic arrival rates $\lambda_{DS\_T}$ and $\lambda_{US\_T}$.
Output: Fully configured Cyclic Sleep Mode following the ECSM framework.
1: Compute the $N_{US}$ and $N_{DS}$ as;
       $N_{DS} = \left(D_{DS} - \mathrm{W_{US}} - \frac{RTT}{2} - T_{init}\right).2\,\lambda_{DS\_T}$
       $N_{US} = \left(D_{US} - \mathrm{W_{US}} - \frac{RTT}{2} - T_{init} - \frac{SI}{2}\right).2\,\lambda_{US\_T}$
2: Divide $N_{US}$ between T1, T2 and T3 traffic classes as;
       $N_{US1} = N_{US} * \frac{ABmin_1}{BW_{ONU}}$
       $N_{US2} = N_{US} * \frac{ABmin_2}{BW_{ONU}}$
       $N_{US3} = N_{US} * \frac{ABmin_3 + ABSur_3}{BW_{ONU}}$
3: Set $N_{US4}$ according to the difference of maximum expected load to the system capacity.
4: Compute ONU mean vacation time ($\bar{V}$) at target US and DS arrival rates $\lambda_{US\_T}$ and $\lambda_{DS\_T}$;
       $\bar{V}_{US} = \frac{N_{US}}{\lambda_{US\_T}}$
       $\bar{V}_{DS} = \frac{N_{DS}}{\lambda_{DS\_T}}$
5: Set $T_{AS} = \min\,(\bar{V}_{DS}, \bar{V}_{US}) - T_{init}$
6: Compute US and DS Buffer clearance times as;
       $\mathrm{T}_{Clear\_US} = \frac{1}{2}(\frac{RTT}{2} + (\frac{125}{10^6})(\frac{N_{US}}{GemSize_{US}})$
       $\mathrm{T}_{Clear\_DS} = \frac{1}{2}(\frac{RTT}{2} + (\frac{125}{10^6})(\frac{N_{DS}}{GemSize_{DS}})$
7: Set $T_{AWARE} = \max\,(\mathrm{T}_{Clear\_US}, \mathrm{T}_{Clear\_US})$
8: Configure all CSM Timers at OLT and ONUs;
       Set $T_{Hold} = 0.5$ ms
       Set $T_{Eri} = T_{AS} + T_{init} + \frac{RTT}{2} + SI$
       Set $T_{Alerted} \geq T_{AS} + T_{AWARE} + T_{init}$
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The US and DS traffic arrival process at the OLT and the ONU may be modeled as an M/G/1 queueing system with the ONU and OLT acting as server, respectively. The ONU stay in AS state may be considered as the vacation time of the server [39]. Therefore, in steps 4 and 5, the ONU T_{AS} is computed based on the value of ONU mean vacation time ($\bar{V}$) for $\lambda_{\mathrm{US\_T}}$ and $\lambda_{\mathrm{DS\_T}}$. This sets the upper limit for ONU to terminate AS state to guarantee compliance to target average delay limits because at lower traffic arrival rates ONU sleep buffer fills slowly and delays the ONU sojourn in AS state and triggering of LWI events. In steps 6 and 7, the sleep aware time (T_{AWARE}) is computed as the maximum of the US and DS buffer clearance time (T_{Clear}) so that ONU is able to clear off the US and DS sleep buffers in Sleep Aware state and able to maximize its sojourn in AS state and avoid frequent interruption of AS state where 155530 bytes and 38880 bytes are the capacity in bytes of the DS and US XGPON frames. The $GemSize_{\mathrm{DS}}$ and $GemSize_{\mathrm{US}}$ is the traffic frame carrying capacity of DS and US frames and can be expressed by Eqs. (1) and (2), where $\mathcal{F}_{\mathrm{avg}}$ is the average traffic frame size. It is possible that the computed value of T_{AWARE} for US and DS is different due to different values of N_{US} and N_{DS}. In that case, ideally, T_{AWARE} with larger value should be chosen but at least it should be greater than T_{AWARE} for US so as not to impact the performance of the DBA process. Thus, the computed values of T_{AS} and T_{AWARE} from Algorithm 1 are optimized and lead to maximum ONU energy savings with delay guarantees.

$$GemSize_{\mathrm{DS}} = \frac{155530}{\mathcal{F}_{\mathrm{avg}}} \tag{1}$$

$$GemSize_{\mathrm{US}} = \frac{38880}{\mathcal{F}_{\mathrm{avg}}} \tag{2}$$

Finally, in the step 8, the values of CSM control timers are computed. The CSM standard do not specify any criteria for the selection of T_{Hold} timer reload value. This is the time an ONU waits before transitioning to Active Free (AF) state when it receives the sleep aware (SA) ON message from the OLT. At minimum it should be one XGPON cycle (125 us). We set it to 0.5 ms as in [40] as being a reasonable choice. The OLT timer T_{Eri} is used to keep check on unusually delayed response from ONU to avoid any communication break. Another OLT timer is T_{Alerted} that determines the OLT sojourn in ALS state when the LWI event has occurred at the OLT. Both the T_{Eri} and T_{Alerted} are set in accordance to the guidelines provided in the XGPON transmission convergence layer standard G.987.3.

4 Sleep assistive DBA scheme

Similar to other IACG scheme, the SA-DBA scheme also comprises of Guaranteed, Surplus and RBW allocation phases. The bandwidth allocation process of SA-DBA is elaborated with the help of flowchart in Fig. 1. During the GPA, it assigns the bandwidth according to the SLA limits and respective queue reports to T2 and T3 traffic classes. Similarly, during the SPA, surplus bandwidth is assigned to T3 and T4, if available, as per their SLA and queue reports.

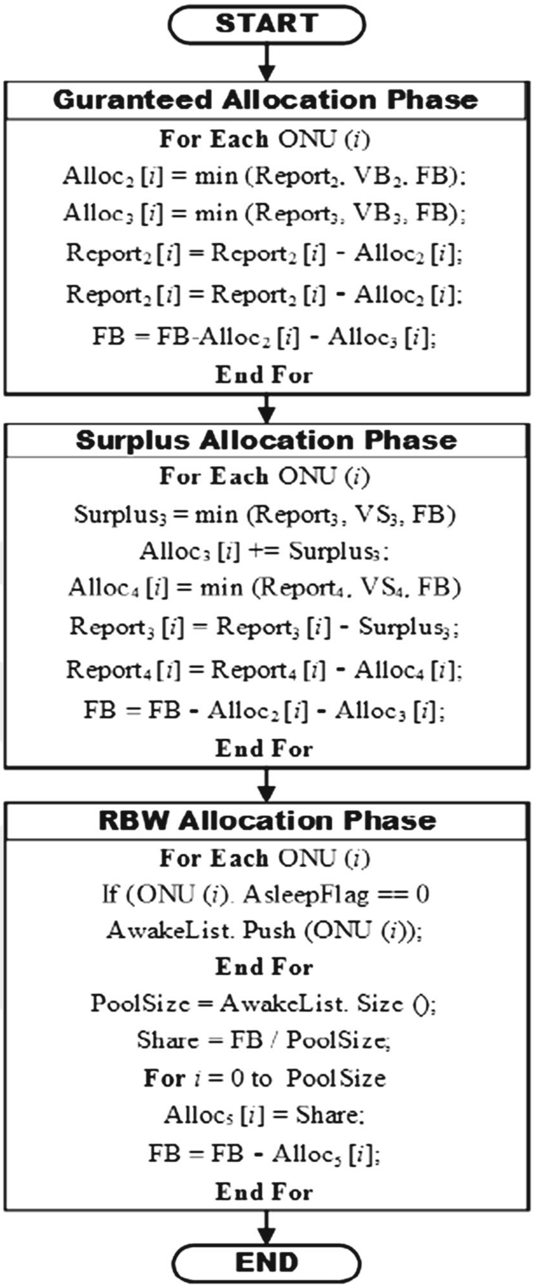

Fig. 1 DBA cycle of SA-DBA scheme

The frame bytes (FB) and the available byte counters VB_2, VB_3, VB_3, VS_3 and VS_4 of T1 to T4 traffic classes are only recharged to maximum bandwidth values; 38880, AB_{min1}, AB_{min2}, AB_{min3}, AB_{sur3} and AB_{sur4}, respectively, after every SI to ensure the committed data rates.

During the RBW phase, IACG assigns any residual bandwidth equally to all the ONUs through the T5 traffic class. This surplus bandwidth is received by each ONU and used by its T2, T3 and T4 traffic classes in a strict class priority order.

However, when the ONUs use the CSM scheme for energy conservation, some ONUs may be in Asleep (AS) state and assigning surplus bandwidth to such ONUs during RBW

Fig. 2 Cyclic sleep state diagram for ONU

Fig. 3 Cyclic sleep state diagram for OLT

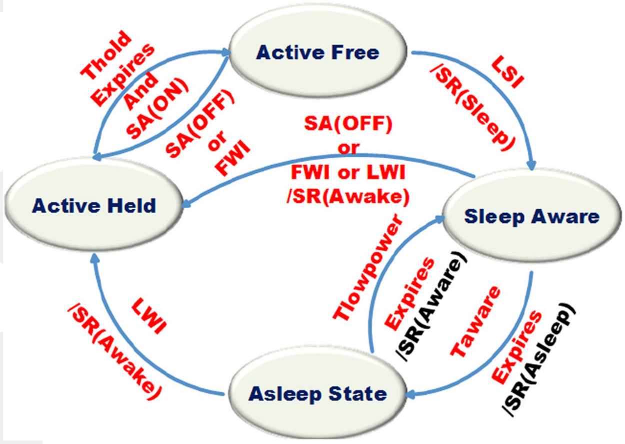

Fig. 4 Cyclic sleep state diagram for OLT

phase will actually be wasted. If this surplus bandwidth can be assigned to the other ONUs in Active state, it will not only reduce the US delays but also increase the overall ONU energy savings. This will happen due to longer AS state time of such ONUs due to early emptying of sleep buffers because of higher bandwidth availability. This will help these ONUs to retain AS state for longer time. This will also lead to comparatively reduced delays of T2, T3 and T4 traffic classes as they will get the opportunity of additional bandwidth through T5 traffic class. The highest impact will be on T2 traffic class, and it will get the highest bandwidth share due to strict class priority based division.

The SA-DBA scheme, therefore, considers only the ONUs in Active state and assigns the surplus bandwidth to only such ONUs during the RBW phase. However, the problem is the correct knowledge of ONUs in AS state at the OLT. With the present CSM process of ONU and OLT, as shown in Figs. 2 and 3, the OLT is exactly aware that when does an ONU enters the AS state during the CSM process. This because of the fact that the OLT only receives the/SR(Sleep) message from the ONU when it enters the AWARE state first time and transitions to low power sleep (LPS) state. The ONU does not inform the OLT when it enters the AS state. Similarly, OLT is also not aware of the ONU state transitions from AS to AWARE state and vice versa during a sleep cycle, while it is in the LPS state, unless the sleep cycle is interrupted though a local wakeup indication (LWI) event at the OLT or ONU. At this point the ONU either sends the/SR(Awake) message to OLT or the OLT transitions to alerted sleep (ALS) state to force the ONU to quit sleep cycle and transition to active held (AH) sate.

To solve this problem, a slight modification is proposed in the standard CSM process of the ONU. The modified ONU sleep state transition diagram is shown in Fig. 4. The ONU sends a SR(Aware) message to OLT when it transitions from AS state to AWARE state and SR(Asleep) message when it is moving to AS state from the AWARE state. Based on these messages, the OLT sets/resets the AsleepFlag [*i*] for the ONU (*i*). These changes do not impact the working of the CSM process and only help OLT to be exactly aware of the ONU AS and AWARE states during the sleep cycle.

In the IACG scheme the ONUs are polled for their queue reports only once which is not enough for the OLT to be accurately aware of ONU bandwidth demand. Moreover, with this approach, an ONU might have to wait for the whole SI period to get the US slot for sending its queue report when awake from AS state during CSM. Since polling every cycle leads to bandwidth waste, therefore, a middle approach is followed by the SA-DBA scheme that all the ONUs are polled in odd cycles during an SI.

5 Simulation setup

Similar to our earlier PON studies [10, 26, 41], the simulation setup comprises of XGPON network in OMNET++ with 16 ONUs with US and DS line rates of 10 and 2.5 Gbps, respectively. The $\mathrm{BW}_{\mathrm{ONU}}$ is set to 200Mbps as also in [25, 41]. The values of RTT and the ONU processing time (P_{D}) are set to be 200 and 35 µs, respectively. The traffic generation follows the Poisson distribution with exponentially varying the inter-arrival time for each value of network load as in [37]. The load is varied from 0.1 to 0.87. Each simulation is run for a long time so that the average value of the recorded mean inter-arrival times converges to within 95% confidence interval. A separate instance of Traffic generator works in each ONU and generates on average the same traffic load. The generated traffic frames follow a triangular distribution with 60%, 20% and 20% probability of 64, 500, and 1500 bytes Ethernet frames with an average frame size $\mathcal{F}_{\mathrm{avg}} = 440$ bytes. The generated traffic frames at each ONU are uniformly distributed between T1 and T4 traffic queues.

For the energy saving analysis of CSM process, only two power levels for ONU are considered; Active and Asleep. It means an ONU is assumed to be fully active and consume 100% power in AH, AF and AWARE states as optical transceiver is ON. In AS state, it is in AS state and consumes only 5% of the full power as in [10, 18]. The CSM parameters and timers are configured using Algorithm 1 with $D_{\mathrm{DS}} = D_{\mathrm{US}} = 56$ ms and $\lambda_{\mathrm{DS\_T}} = 200$ Mbps per ONU and $\lambda_{\mathrm{US\_T}} = \frac{\lambda_{DS_T}}{4}$. The buffer sizes for each of T1, T2, T3 and T4 traffic classes are computed from step 1. Thus, the N_{DS} and N_{US} are computed as 6125 frames and 1528 frames with. Further from step 2, the N_{US1}, N_{US2}, N_{US3} and N_{US4} are computed as 153, 687,687,198 frames. The complete details of the DBA-related parameters and rest of the CSM parameters are given in Table 2.

Table 2 Additional simulation parameters

Parameter	Values/details
λ_{DS}	Varied from 932 frames/s to 38750 frame/s corresponding to a load variation from 13 Mbps to 560 Mbps per ONU as in [38, 42]
λ_{US}	$\lambda_{\mathrm{DS}}/4$
T_{AWARE}	3 ms
T_{AS}	56–2 ms = 54 ms
T_{Init}	2 ms
T_{Hold}	0.5 ms
T_{ERI}	$T_{\mathrm{AS}} + T_{\mathrm{init}} + \mathrm{SI} + \mathrm{RTT} = 57$ ms
T_{ALERTED}	Should be $\geq (T_{\mathrm{AS}} + T_{\mathrm{SLA}} + T_{\mathrm{init}}) = 60$ ms
$\mathrm{AB}_{\mathrm{min1}}$	= 315 with $SI_{\mathrm{min1}} = 5$ (20 Mbps Bandwidth)
$\mathrm{AB}_{\mathrm{min2}}$	= 7030 with $\mathrm{SI}_{\mathrm{min2}} = 5$ (90 Mbps Bandwidth)
$\mathrm{AB}_{\mathrm{min3}}$	= 3515 with $SI_{\mathrm{min3}} = 5$ (45 Mbps Bandwidth)
$\mathrm{AB}_{\mathrm{sur}_3}$	= 3515 with $\mathrm{SI}_{\mathrm{max3}} = 5$ (45 Mbps Bandwidth)
$\mathrm{AB}_{\mathrm{sur4}}$	= 315 with $\mathrm{SI}_{\mathrm{max4}} = 5$ (100 Mbps Bandwidth)

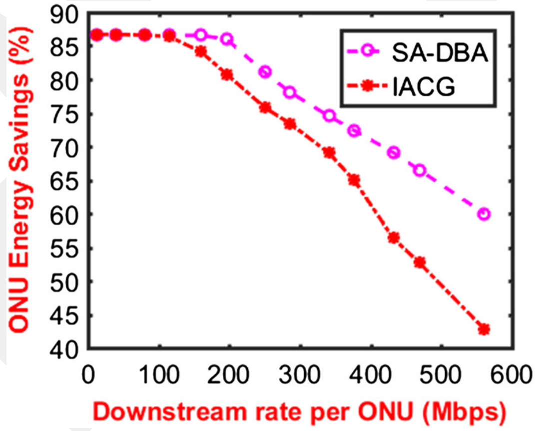

Fig. 5 Average ONU energy savings

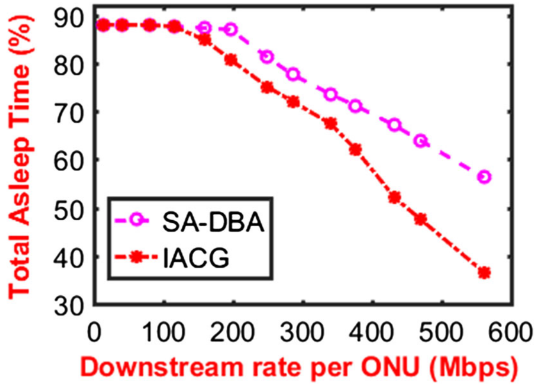

Fig. 6 Average ONU energy savings

6 Results and discussion

The performance results for both IACG and SA-DBA schemes for T1, T2, T3 and T4 traffic classes are recorded from the simulation. The results comprise of average US and DS delays, average ONU energy savings, average ONU AS state time, average US and DS Delay variance and are shown in Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16.

Both IACG and SA-DBA perform quite close at very low traffic loads and show very high energy savings of 89% as shown in Fig. 5. The high energy savings are due to ONU being mostly in AS state as evident from Fig. 6. The energy savings decrease as traffic load increases due to the reduction of AS state time of ONU. However, with an increase in traffic load, the SA-DBA shows higher energy savings compared to IACG scheme and shows 40% higher savings at a load of 560Mbps per ONU with 53% higher average AS state time for ONUs. This is because of higher bandwidth assignment in

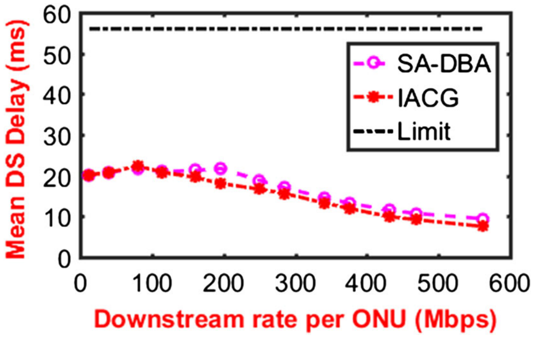

Fig. 7 Average DS delay

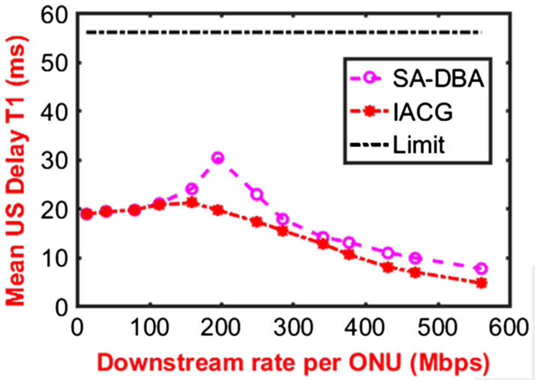

Fig. 8 Average US delay of T1 traffic class

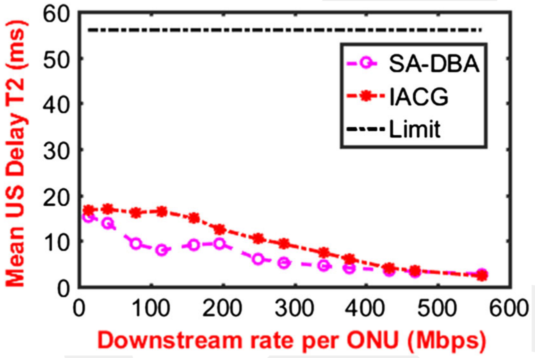

Fig. 9 Average US delay of T2 traffic class

RBW phase which results in higher ONU AS state time and, thus, higher energy savings (ES%). The ES% is computed as a percentage of Active state energy consumption using Eq. (3), where the simulation time (T_{Sim}) is equal to the sum of T_{AS}, T_{SLA} and T_{Active} which is the sum of both T_{AF} and T_{AH}.

$$\text{ES\%} = 1 - \left(\frac{T_{\text{AS}} * P_{\text{AS}} + T_{\text{SLA}} * P_{\text{AWARE}} + T_{\text{Init}} * P_{\text{AH}} + T_{\text{Active}} * P_{\text{AF}}}{T_{\text{Sim}} * P_{\text{A}}}\right) \tag{3}$$

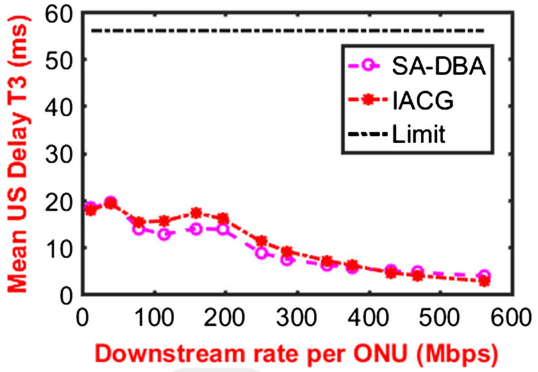

Fig. 10 Average US delay of T3 traffic class

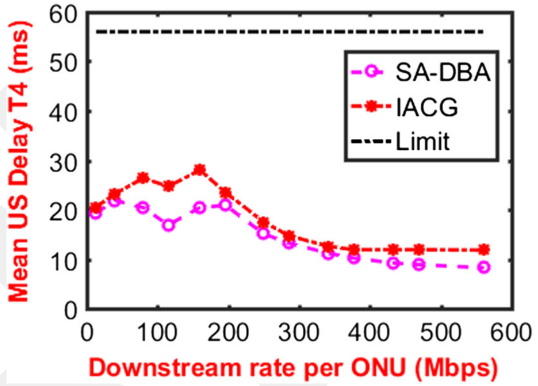

Fig. 11 Average US delay of T4 traffic class

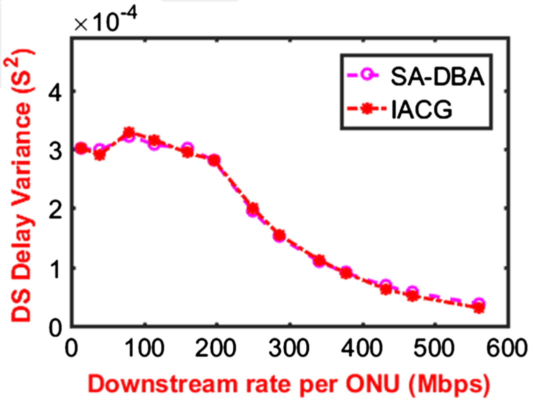

Fig. 12 Average DS delay variance

Since in both DBA schemes, the bandwidth assignment is same to the T1 and DS traffic; thus, the prolonged AS state time in SA-DBA leads to slightly higher delay of DS and US T1 traffic when traffic load increases as shown in Figs. 7 and 8. The highest increase in delay is at 200 Mbps traffic load due to highest traffic queuing as the sleep buffer gets full. However, further increase in traffic load results in a reduction of AS state time due to triggering of LWI events. The delay of SA-DBA is observed to higher due to higher AS state time as evident from Fig. 6.

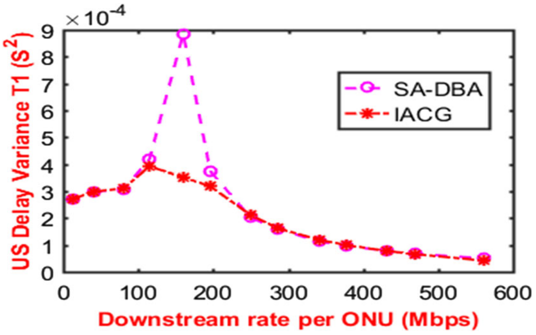

Fig. 13 Average US delay variance T1 traffic class

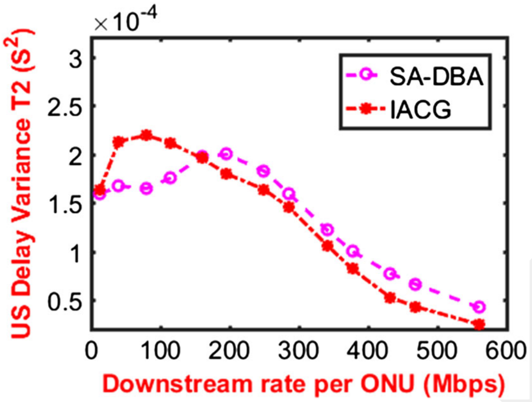

Fig. 14 Average US delay variance of the T2 traffic class

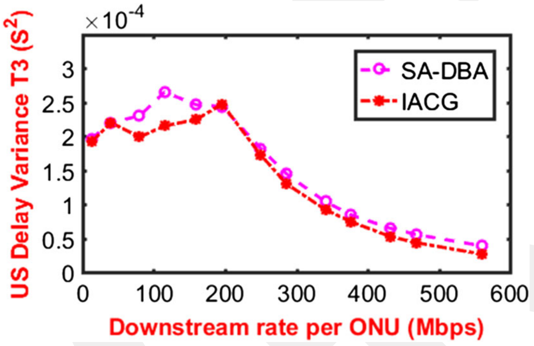

Fig. 15 Average US delay variance of T3 traffic class

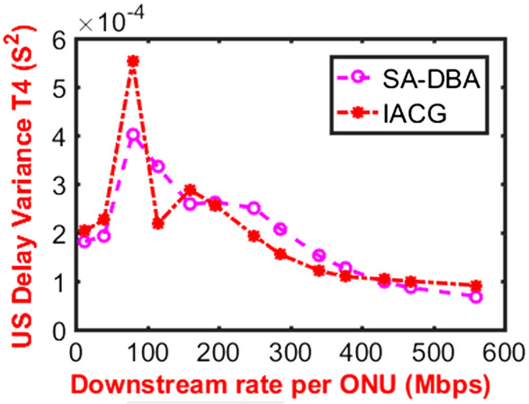

Fig. 16 Average US delay variance of T4 traffic class

However, due to additional bandwidth assignment in RBW phase in SA-DBA, the T2, T3, and T4 traffic classes get comparatively higher bandwidth assignments at medium and low traffic loads which results in comparatively lower delays for SA-DBA as evident from Figs. 9, 10, and 11. However, in both DBA schemes, all the US and DS average delays adhere to the set target average delay limit of 56 ms which shows the success of ECS framework. A slight dip is seen in T2, T3 and T4 delay for SA-DBA at the traffic load of 100 Mbps due to probably extra bandwidth assignment by the SA-DBA scheme from the share of the Asleep ONUs compared to IACG scheme. After the traffic load of 200 Mbps, all the delays start decreasing. This is because of reduction in ONU AS state time due to ONU sleep buffers getting filled early and causing termination of sleep cycles due to triggering of LWI events, as evident from Fig. 6.

All the delay variance results for SA-DBA, except T2, are observed to be comparatively higher than the IACG scheme. This is because of the random availability and assignment of the excess bandwidth by SA-DBA in RBW phase as all the ONUs execute sleep process independently and randomly and it is least likely that all enter the AS state simultaneously. For both schemes, the delay variance is higher at low traffic loads and reduces with the increase in traffic load due to higher ONU sleep activity as evident from Fig. 6. For T2 it remains lower due to the utilization of RBW in strict class priority which mostly results in the utilization of excess bandwidth by T2 and thus lower bandwidth assignment to T3 and T4 traffic class, leading to higher delay variance compared for T2 and T3, especially at low traffic loads due to higher sleep activity. The DS delay variance for both schemes remains the same as it is not impacted by the DBA scheme. The rise in delay variance for T1 at 200 Mbps is due to highest queuing which caused a rise in an average delay of T1 as evident from Fig. 8 as well as increased delay variance. Overall, all the delay variance results are observed to be low and do not exceed 1 ms.

Thus, the combination of SA-DBA with ECS framework shows an optimized performance for the set target average delay limits with very high energy savings for the ONUs and comparatively lower delay and insignificant increase in US delay variance for the ONUs.

7 Conclusion and future work

This study presents an energy efficient DBA scheme for GPON and XGPON networks. The proposed SA-DBA scheme utilizes the unused bandwidth of the Asleep ONUs and assigns it as a surplus bandwidth to the Active ONUs. This results in reduced traffic queue sizes at the ONUs and thus leads to higher AS state time due to infrequent interruption of the sleep cycle. This also leads to higher average energy savings per ONU and reduced upstream delays and variance results for T2, T3, and T4 traffic classes. However, the DS delay and variance slightly increases at lower traffic loads due to higher ONU Asleep state time as they do not utilize the DBA mechanism. In our future work, we will investigate a similar DBA scheme for TWDM PON.

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References

[1] Sanou, B.: ICT Facts and Figures 2017. Switzerland, Geneva (2017)

[2] Effenberger, F.J.: Industrial trends and roadmap of access. J. Lightwave Technol. **35**(5), 1142–1146 (2017)

[3] Klein, T.E., Richard, P.: ICT energy challenges, impact and solutions. In: 19th International ICIN Conference—Innovations in Clouds, Internet and Networks, pp. 281–286

[4] Conti, J., Holtberg, P., Diefenderfer, J., LaRose, A., Turnure, J.T., Westfall, L.: International energy outlook 2016 with projections to 2040. In: Annual report by the US Energy Information Administration (EIA), vol. DOE/EIA-04, US EIA, Washington, D.C 20585, pp. 1–290 (2016)

[5] Mills, M.P.: The Cloud Begins with Coal: Big data, Big Networks, Big infrastructure, and Big power—An Overview of the Electricity use by the Global Digital Ecosystem, pp. 1–48. Digital Power Group, New York (2013)

[6] Andrae, A., Edler, T.: On global electricity usage of communication technology: trends to 2030. Challenges **6**(1), 117–157 (2015)

[7] Butt, R.A., Hasunah Mohammad, S., Idrus, S.M., Rehman, S.U.: Evolution of access network from copper to PON—Current status. ARPN J. Eng. Appl. Sci. **10**(18), 1–10 (2015)

[8] Mahloo, M., Chen, J., Wosinska, L.: PON versus AON: which is the best solution to offload core network by peer-to-peer traffic localization. Opt. Switch. Netw. **15**, 1–9 (2015)

[9] Abbas, H.S., Gregory, M.A.: The next generation of passive optical networks: a review. J. Netw. Comput. Appl. **67**, 53–74 (2016)

[10] Butt, R.A., Idrus, S.M., Qureshi, K.N., Shah, P.M.A., Zulkifli, N.: An energy efficient cyclic sleep control framework for ITU PONs. Opt. Switch. Netw. **27**, 7–17 (2018)

[11] Valcarenghi, L. et al.: Energy efficiency in optical access networks. In: Italian Networking Workshop, pp. 38–40 (2011)

[12] Dhaini, A.R., Ho, P.H., Shen, G.: Toward green next-generation passive optical networks. IEEE Commun. Mag. **49**(11), 94–101 (2011)

[13] Shi, L., Mukherjee, B., Lee, S.S.: Energy-efficient PON with sleep-mode ONU: progress, challenges, and solutions. IEEE Netw. **26**(2), 36–41 (2012)

[14] Nikoukar, A., Hwang, I., Liem, A.T., Wang, C., Lin, Y., Golderzehi, V.: A new QoS-aware green dynamic bandwidth allocation in ethernet passive optical network. In: IEEE International Conference on Intelligent Green Building and Smart Grid (IGBSG) (2014)

[15] Ahmed, M., Ahmad, I., Habibi, D.: Green wireless-optical broadband access network: energy and quality-of-service considerations. J. Opt. Commun. Netw. **7**(7), 669 (2015)

[16] Khotimsky, D.A., Zhang, D., Yuan, L., Hirafuji, R.O.C., Member, S., Campelo, D.R.: Unifying sleep and doze modes for energy-efficient PON systems. IEEE Commun. Lett. **18**(4), 688–691 (2014)

[17] Lee, S.S.W., Li, K.-Y.: Adaptive state transition control for energy-efficient gigabit-capable passive optical networks. Photon Netw. Commun. **30**(1), 71–84 (2015)

[18] Hirafuji, R.O.C., Cunha, K.B., Campelo, D.R., Dhaini, A.R., Khotimsky, D.A.: The watchful sleep mode: a new standard for energy efficiency in future access networks. IEEE Commun. Mag. **58**(3), 150–157 (2015)

[19] Mahmud, Y.A., Radzi, N.A.M., Abdullah, F., Din, N.M.: Fuzzy-logic based NSR DBA for upstream GPON. In: EEE 12th Malaysia International Conference on Communications (MICC), pp. 169–174 (2015)

[20] Bang, H., Kim, S., Lee, D.-S., Park, C.-S.: Dynamic bandwidth allocation method for high link utilization to support NSR ONUs in GPON. In: 12th International Conference on Advanced Communication Technology (ICACT), vol. 1, pp. 1–6 (2010)

[21] Walid, A., Chen, A.: Efficient and dynamic bandwidth allocation for non-status reporting gigabit passive optical networks (GPON). In: IEEE International Conference on Communications, vol. 2015, pp. 1000–1005 (2015)

[22] He, R., Xie, H., Fang, X.: A long-term proportional fair dynamic bandwidth allocation scheme for EPON. In: 2016 25th Wireless and Optical Communication Conference (WOCC), pp. 1–5 (2016)

[23] Hossen, M., Saha, S.: Thread guaranteed algorithm for real time traffic in multi-threaded polling of PON-based open access network. In: International Conference on Electrical, Computer and Communication Engineering (ECCE), pp. 290–295 (2017)

[24] Kanonakis, K., Tomkos, I.: Offset-based scheduling with flexible intervals for evolving GPON networks. J. Lightwave Technol. **27**(15), 3259–3268 (2009)

[25] Han, M.S., Yoo, H., Lee, D.S.: Development of efficient dynamic bandwidth allocation algorithm for XGPON. ETRI J. **35**(1), 18–26 (2013)

[26] Butt, R.A., Idrus, S.M., Rehman, S.-U., Shah, P.M.A., Zulkifli, N.: Comprehensive polling and scheduling mechanism for long reach gigabit passive optical network. J. Opt. Commun. (2017). https://doi.org/10.1515/joc-2017-0026

[27] Butt, R.A., Idrus, S.M., Zulkifli, N., Ashraf, M.W.: A survey of energy conservation schemes for present and next generation passive optical networks. J. Commun. **13**(3), 129–140 (2018)

[28] Yan, Y., et al.: Energy management mechanism for ethernet passive optical networks (EPONs). In: IEEE International Conference on Communications (ICC), pp. 1–5 (2010)

[29] Van Pham, D., Valcarenghi, L., Chincoli, M., Castoldi, P.: Experimental evaluation of a sleep-aware dynamic bandwidth allocation in a multi-ONU 10G-EPON testbed. Opt. Switch. Netw. **14**(Part1), 11–24 (2014)

[30] Dixit, A., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: ONU power saving modes in next generation optical access networks: progress, efficiency and challenges. Opt. Express **20**(26), B52–B63 (2012)

[31] Dixit, A., Lannoo, B., Colle, D., Pickavet, M., Demeester, P.: Energy efficient dynamic bandwidth allocation for ethernet passive optical networks: overview, challenges, and solutions. Opt. Switch. Netw. **18**, 169–179 (2015)

[32] Li, C., Guo, W., Hu, W., Xia, M.: Energy-efficient dynamic bandwidth allocation for EPON networks with sleep mode ONUs. Opt. Switch. Netw. **15**, 121–133 (2015)

[33] Nikoukar, A.A., Hwang, I.S., Liem, A.T., Wang, C.J.: QoS-aware energy-efficient mechanism for sleeping mode ONUs in enhanced EPON. Photon Netw. Commun. **30**(1), 59–70 (2015)
[34] Dias, M.P.I., Wong, E.: Sleep/doze controlled dynamic bandwidth allocation algorithms for energy-efficient passive optical networks. Opt. Express **21**(8), 9931–9946 (2013)
[35] Wong, S.W., Valcarenghi, L., Yen, S.H., Campelo, D.R., Yamashita, S., Kazovsky, L.: Sleep mode for energy saving PONs: advantages and drawbacks. In: IEEE Globecom Workshops, pp. 1–6 (2009)
[36] Butt, R.A., Idrus, S.M., Qureshi, K.N., Zulkifli, N., Mohammad, S.H.: Improved dynamic bandwidth allocation algorithm for XGPON. J. Opt. Commun. Netw. **9**(1), 87–97 (2017)
[37] Butt, R.A., Idrus, S.M., Zulkifli, N., Ashraf, M.W.: Comprehensive bandwidth utilization and polling mechanism for XGPON. Int. J. Commun. Syst. **31**, e3475 (2017)
[38] Butt, R.A., Idrus, S.M., Qureshi, K.N., Shah, P.M.A., Zulkifli, N.: An energy efficient cyclic sleep control framework for ITU PONs. Opt. Switch. Netw. **27**, 7–17 (2018)
[39] Bokhari, M., Sohail, M., Kasi, J.K., Kasi, A.K.: Performance analysis of passive optical networks with energy saving through the integrated sleep mode. Opt. Switch. Netw. **21**, 16–30 (2016)
[40] Skubic, B., Hood, D.: Evaluation of ONU power saving modes for gigabit-capable passive optical networks. IEEE Netw. **25**(2), 20–24 (2011)
[41] Butt, R.A., Idrus, S.M., Qureshi, K.N.: Improved dynamic bandwidth allocation algorithm for XGPON. J. Opt. Commun. Netw. **9**(1), 87–97 (2017)
[42] Hirafuji, R.O.C., Dhaini, A., Khotimsky, D.: Energy efficiency analysis of the watchful sleep mode in next-generation passive optical networks. In: IEEE Symposium on Computers and Communication (ISCC), pp. 689–695 (2016)

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