Improved Dynamic Bandwidth Allocation Algorithm for XGPON

Rizwan Aslam Butt, Sevia Mahdaliza Idrus, Kashif Naseer Qureshi,
Nadiatulhuda Zulkifli, and Siti Hasunah Mohammad

***Abstract*—Passive optical networks (PONs) require a dynamic bandwidth allocation (DBA) algorithm at the optical line terminal for efficient utilization of upstream bandwidth among the optical network units (ONUs) as per the quality of service requirements for each traffic class defined by PON standardizing bodies. The GigaPON access network (GIANT) was the first International Telecommunication Union compliant DBA algorithm, which is further improved by Immediate Allocation with Colorless Grant (IACG) and Efficient Bandwidth Utilization (EBU) algorithms. However, the polling mechanism of IACG and EBU may not report the true bandwidth demand of ONUs during a service interval. Furthermore, ONU scheduling mechanisms give preference to best effort traffic over the assured traffic during recursive allocation cycles in a service interval, which results in an increase in upstream delays for the assured traffic class. This paper presents an improved bandwidth utilization (IBU) algorithm, which rectifies these deficiencies with a novel polling and scheduling mechanism. Experimental results show that IBU improves the mean of upstream delays of type 2 traffic up to 98%, 93%, and 76% and up to 99%, 92%, and 73% for type 3 traffic compared to the GIANT, IACG, and EBU algorithms, respectively. IBU also shows the least frame loss compared to these state-of-the-art algorithms.**

***Index Terms*—DBA; Dynamic bandwidth allocation; Efficient bandwidth utilization; PON; XGPON.**

I. INTRODUCTION

The International Telecommunication Union (ITU) reported in 2015 that information and communication technologies (ICTs) have rapidly expanded [1]. Growth of 46% in Internet usage, 10.8% for fixed broadband, and 47% for mobile services subscriptions was recorded [2]. In the fixed broadband, passive optical networks (PONs) have emerged as an attractive optical-fiber-based broadband network due to their impressive characteristics, such as high bandwidth, long coverage, low power consumption, and easy deployment [3]. PONs are passive in nature except the optical line terminal (OLT) at the central office and the optical network unit (ONU) at the user end. The rest of the network does not require active components in the access part. The passive nature of these networks makes them cost effective. From a single PON port in an OLT, up to 32–64 users can be serviced by splitting the optical power with the help of an optical power splitter. Currently, GPON and EPON are the most widely deployed PONs. These PONs use a fixed 1490 nm wavelength for a downstream (DS) link and 1310 nm for an upstream (US) link on the same fiber link. The DS frames from the OLT side are sent as a broadcast to all ONUs. Each ONU receives all the frames but accepts only the related frame and discards all others. However, for the US link, if all ONUs send their frames simultaneously to the OLT at the same wavelength, then all signals will collide. Therefore, an arbitration mechanism is required at the OLT to serve each ONU one by one in a time division multiplexed (TDM) manner.

A simple arbitration mechanism is equal and fixed time-slot allocation to ONUs for US transmission. However, this approach has a disadvantage that the ONU with less bandwidth requirement wastes bandwidth while others with higher bandwidth requirement are restricted. Therefore, for efficient utilization of US bandwidth among ONUs, a dynamic bandwidth allocation (DBA) algorithm is required that can look at the ONU demands and allocate US bandwidth accordingly. With an efficient DBA scheme, it is also possible for an operator to oversubscribe users with best effort bandwidth commitment and thus enhance its revenues while adhering to the quality of service (QoS) requirements as per subscriber line agreements (SLAs).

A PON network is required to support multiple traffic types with different delay bounds, such as voice, video, VoIP, data, and leased lines. The ITU categorizes PON traffic into four classes, namely, type 1 (T1), type 2 (T2), type 3 (T3), and type 4 (T4), as shown in Table I [4,5]. In order to carry multiple traffic types simultaneously, ITU PONs (GPON/XGPON) have a specific data structure called transmission container (TCONT). Each TCONT has a unique allocation ID (Alloc-ID) to identify different traffic types [6,7]. Every ONU maintains a separate queue for each type of traffic. Each traffic class is uniquely identified by an Alloc-ID, which is assigned by the OLT during ONU initialization. During US bandwidth allocation, OLT uses these Alloc-IDs to distinguish between different traffic types and allocates bandwidth accordingly.

Neither IEEE and ITU PON standards [6,8] specify any particular DBA algorithm and leave this open for the

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R. A. Butt, S. M. Idrus (e-mail: sevia@fke.utm.my), N. Zulkifli, and S. H. Mohammad are with the Electrical Engineering Department, University of Technology Malaysia, Johor Bahru, Skudai 81300, Johor, Malaysia.

K. N. Qureshi is with the Computer Science Department, University of Technology Malaysia, Johor Bahru, Skudai 81300, Johor, Malaysia.

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TABLE I
ITU TRAFFIC TYPES FOR PON

Type	Application	Bandwidth	Service Parameters
T1	Leased lines/CBR	Fixed	SI_{max}, AB_{min}
T2	Voice/video	Assured	SI_{max}, AB_{min}
T3	VBR/best effort	No guarantee	SI_{max}, AB_{min} SI_{min}, AB_{sur}
T4	Better than best effort	No guarantee	SI_{max} (for polling only), SI_{min}, AB_{sur}

vendors. This has triggered a lot of research on an efficient DBA design for PON. However, most of the studies have chosen IEEE PONs. A detailed review of DBA algorithms for EPON is available in [8–10]. To the best of our knowledge, only a few studies have selected GPON/XGPON DBA [5,11–15]. The reason behind this might be its strict bandwidth requirements for a service class in ITU PONs compared to IEEE PONs. Another reason for more research on IEEE PONs is their close resemblance to the Ethernet frame structure, which makes it easier to study and test. On the other hand, ITU PONs have an entirely different frame structure and require a new test bed design. However, DBA algorithms for IEEE PONs are not compatible with ITU PONs because IEEE PONs are neither synchronous nor have a fixed length. On the other hand, ITU PONs have a fixed 125 μs length for both US and DS frames and are synchronized. Moreover, IEEE PONs use different frame formats for communication, like GATE and REPORT, while ITU PONs use only a single frame format for US and DS communications. Therefore, this study focuses on an efficient DBA algorithm design that is compatible with ITU PONs.

GIANT [13] was the first DBA algorithm for ITU PONs. Its bandwidth scheduling mechanism includes two phases, namely, guaranteed phase allocation (GPA) and surplus phase allocation (SPA). Both GPA and SPA are executed during a service interval (SI). It is measured in number of XGPON cycles, where each cycle is fixed to 125 μs. To keep count of SI, GIANT uses an SI timer. Therefore, GPA and SPA in GIANT are executed whenever the timer expires. When any new frame is arriving, it has to wait for a period of SI to get the transmission time slot for US transmission. IACG [5] improves GIANT by repeating GPA and SPA in every XGPON cycle during an SI. EBU [14,15] further improves IACG by allowing the available byte counter (VB) to become negative and indicate unfulfilled demand of overloaded ONU TCONTs during GPA and SPA. The update operation of EBU assigns the remaining unassigned bandwidth of a traffic class to such TCONTs. Thus, it equalizes the bandwidth allocation between the overloaded and underloaded TCONTs belonging to the same traffic class. However, both IACG and EBU suffer from an inefficient polling and scheduling mechanism. The polling mechanism of EBU and IACG may not report the true ONU demand to the OLT if channel delay varies from the expected, for example, due to increased joints in the fiber link caused by fiber cuts. It also cannot report true ONU demand for the next SI if allocation is sent once, as in GIANT and IBU. This results in inaccurate bandwidth allocation. The scheduling mechanism of IACG and EBU is also flawed. It may give preference to T4 traffic over T2 and T3 during an SI. This leads to increased US delays of T2 and T3, which should not happen as T2 and T3 are higher priority traffic classes.

In this paper, we address these problems by proposing a novel polling mechanism to collect accurate ONU queue reports and a modified scheduling mechanism to always ensure priority for T2 and T3 traffic during GPA and SPA phases. IBU strictly maintains the priority order of traffic classes during the DBA process and makes sure that T4 traffic TCONTs always get whatever remains at the end of the SI. This approach reduces bandwidth allocation of T4, especially at higher traffic loads, but this is acceptable for the best effort traffic class.

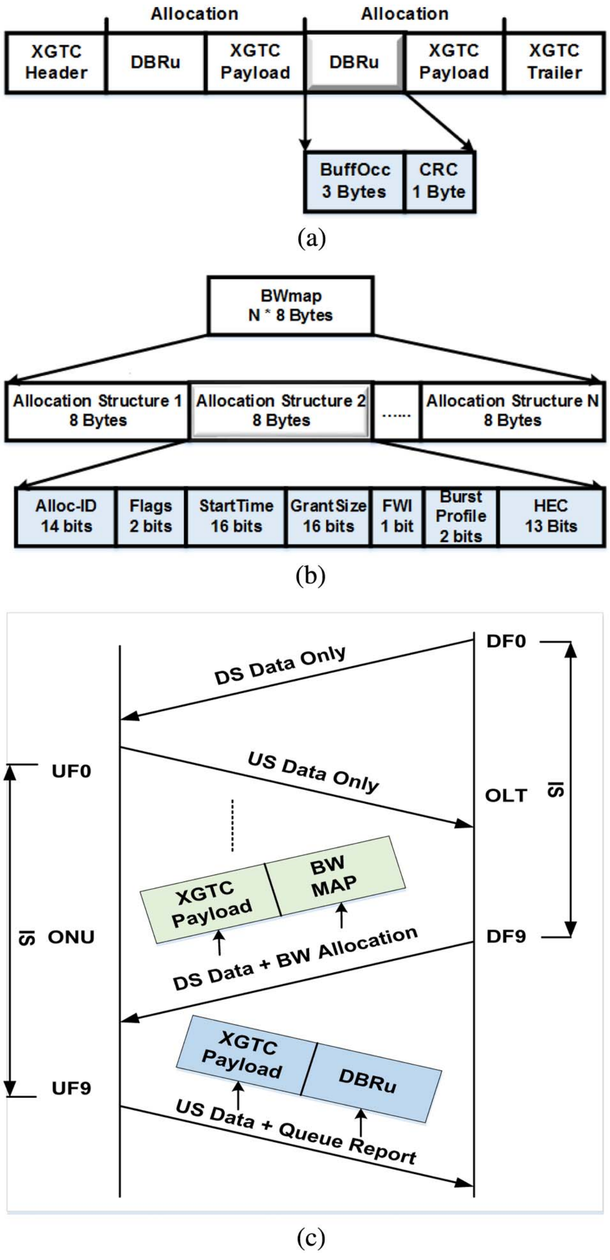
The rest of the paper is organized as follows. Section II defines the target PON system, Section III reviews the closely related work, Section IV describes the limitations of the EBU algorithm, Section V presents the new algorithm, and in Section VI, results are presented and discussed. Finally, Section VII concludes the paper with future research directions.

II. SYSTEM DESCRIPTION

A typical TDM PON includes an OLT, a power splitter, and 32 to 64 ONUs. Unlike EPON and its successor GEPON, GPON and its successor XGPON, which are inspired from older ATM PONs (APONs), use a specific frame structure termed the GPON encapsulation method (GEM) and XGEM for GPON and XGPON, respectively. Both the upstream frame (UF) and downstream frame (DF) in ITU PONs have a fixed 125 μs size. To support multiple traffic types, XGPON encapsulates respective traffic in a TCONT structure, which is identified by an Alloc-ID. A TCONT is further comprised of multiple GEM payloads, where each payload has a GEM header. The payload length indicator (PLI) field of the GEM header indicates the length of the payload that is being carried and is uniquely identified by a Port-ID. This Port-ID serves the same purpose as the port number in transmission control protocol (TCP). The payload type indicator (PTI) provides support for fragmentation. It indicates whether or not the frame fragment is the end of a frame. With the help of the Port-ID and PTI fields, the OLT can reassemble the frames that arrive from an ONU. Header error control (HEC) is used for error correction of the carried payload [7].

For US bandwidth assignment management, the ITU standard specifies two options for the OLT DBA mechanism, namely, non-status reporting (NSR-DBA) and status reporting (SR-DBA) [16]. In the first case, the OLT estimates the ONU requirements from the received traffic and allocates bandwidth accordingly. In the second case, ONUs are required to maintain separate queues for each traffic type and report their queue sizes to the OLT periodically using the dynamic bandwidth report (DBRu) field of the US frames. The OLT computes the US bandwidth allocations for all the TCONTs of ONUs based on the received reports using a DBA algorithm. It then sends bandwidth allocations to the ONUs via the bandwidth map (BWmap) field of the DS frames. Sending a queue report in the US frame from an ONU to an OLT in GPON requires 4 or 2 bytes, which depends upon either mode 2 or mode 1 in the piggyback reporting style [7]. Figures 1(a) and 1(b) show the DBRu and BWmap fields in the UF and DF of XGPON, respectively, and Fig. 1(c) shows a running DBA process.

Bandwidth allocation by a DBA algorithm means the time assigned to an ONU to engage the US media for sending its traffic to the OLT. However, this time in ITU PONs is allocated to TCONT (i) of an ONU (j) in terms of the number of bytes based on its type and received queue report (i), where i could be 1, 2, 3, or 4 depending upon traffic class, while j represents total number of ONUs. Ideally, the DBA algorithm should allocate the bandwidth to ONUs in every DS frame. However, this makes the polling mechanism complex as it requires the OLT to remember the allocations sent to a TCONT (i) from the time when the BWmap is sent until the report (i) is received from the ONU. Hence, IBU sends allocation once during an SI, as in GIANT, but in IBU ONU uses the received allocation for all the cycles until the next allocation is received in the coming SI. The ONU uses a local counter to keep track of the SI. At the OLT, two separate timers are required to keep track of the SI. In GPA, it uses an $\mathrm{SI}_{\mathrm{max\_Timer}}$, while in the SPA phase, it uses $\mathrm{SI}_{\mathrm{min\_Timer}}$. GPA is always executed first where the minimum allocation bytes ($\mathrm{AB}_{\mathrm{min}}$) are allocated to T1, T2, and T3 traffic. Then, in the surplus phase, additional bandwidth ($\mathrm{AB}_{\mathrm{sur}}$) is assigned to T3 and T4, which is proportional to their demands and availability. T1 traffic is always assigned a fixed allocation and its queue report is not required from the ONU.



(a)

(b)

(c)

Fig. 1. DBA process. (a) DBRu report in the UF. (b) BWmap in the DF. (c) Queue reporting and DBA process.

$\mathrm{AB}_{\mathrm{min}}$ for T1 and T2 is assigned in accordance with the committed information rate (CIR) of T1 and peak information rate (PIR) of T2. For T3, it is assigned based on the guaranteed information rate (GIR) with the condition that GIR is one-third of the sum of the PIR and CIR. However, the sum of PIR and GIR should not exceed system capacity, as shown by

$$\mathrm{PIR} + \mathrm{CIR} \le \mathrm{FB}. \tag{1}$$

Although it depends on operator tariff policy, it is, however, a good practice to keep the sum of the PIR and CIR less than the system capacity so that the best effort traffic gets some room to work, especially under higher traffic load conditions [13]. Total UF delay depends upon four factors as given by

$$\mathrm{UFD} = Q_D + P_D + T_D + \mathrm{SI}, \tag{2}$$

where Q_D is the queuing delay experienced by the frame, P_D is the delay in receiving the queue reports, and T_D is the US channel delay. Except for Q_D, the factors are constant, which increases as the traffic load increases, and the service rate is less than the traffic arrival rate. Therefore, a US frame delay solely depends upon the efficiency of the DBA algorithm. Service rate here means the number of available bytes for a particular TCONT (i) of an ONU (j) that are allocated by the DBA process during an SI.

III. Related Work

The GIANT algorithm was published in 2004 [3] and its first implementation using a field-programmable gate array (FPGA) was demonstrated in 2006 in [10]. It utilizes the service parameters of Table I. During an SI, it polls the ONUs only once for queue report collection and executes GPA and SPA when $\mathrm{SI}_{\mathrm{max\_Timer}}$ and $\mathrm{SI}_{\mathrm{min\_Timer}}$ expire. If traffic frames for an ONU TCONT arrive just after it has sent its queue report, they have to wait until the SI timer expires to get a US bandwidth allocation, resulting in increase of US delays. After the SI timer expires, GIANT recharges the SI timer to $\mathrm{SI}_{\mathrm{min}}$ and $\mathrm{SI}_{\mathrm{max}}$ and VB (i) to $\mathrm{AB}_{\mathrm{min}}$ or $\mathrm{AB}_{\mathrm{sur}}$ depending upon the type of TCONT. The guaranteed service rate is, therefore, $\mathrm{AB}_{\mathrm{min}}/\mathrm{SI}_{\mathrm{min}}$ and the surplus rate is $\mathrm{AB}_{\mathrm{sur}}/\mathrm{SI}_{\mathrm{min}}$. GIANT uses a value of 10 for $\mathrm{SI}_{\mathrm{min}}$ and $\mathrm{SI}_{\mathrm{max}}$. It allocates a minimum bandwidth to T4 TCONTs during GPA for receiving a DBRu report.

IACG improves GIANT by allowing GPA and SPA execution in every frame duration until the VB (i) for a TCONT (j) is greater than zero. Although IACG increases GPA and SPA frequency and sends allocation to ONUs in every DS frame but the VB (i), the counters are recharged only once during an SI to maintain the agreed data rate for each traffic class. Therefore, compared to GIANT, the mean US delays improve for all traffic types. The polling frequency of IACG is similar to GIANT, except that it does not assure the minimum polling bandwidth for T4 traffic TCONTs. It also introduces the idea of dividing the unused bandwidth among all the ONU TCONTs equally at the end of a DBA cycle, termed colorless grant (CG). IACG also introduces a novel polling mechanism for an accurate and updated ONU queue report collection. However, this method may not report the true demand of ONU TCONTs for the next SI. A detailed discussion follows in Section IV. IACG uses separate SI timers and byte counters for all TCONTs, which could be computationally expensive with limited processing resources. Therefore, the same authors have also presented a revised scheduling procedure for IACG with a single byte counter and an SI timer for all types of TCONTs in [14].

EBU introduces the idea of underloaded and overloaded TCONTs. Unlike GIANT and IACG, it allows the byte counter VB (i) of a TCONT (i) to become negative if the report (i) for the TCONT (i) is greater than its VB (i) to indicate that its demand is higher than the maximum allowed allocation $\mathrm{AB}_{\mathrm{min}}$ (i). To achieve this, EBU subtracts the report (i) from VB (i) whenever bandwidth is allocated to a TCONT (i) of an ONU (j). In contrast, in IACG, the allocation assigned is subtracted from the VB (i) and therefore VB (i) could never be negative. After the GPA and SPA, it sums all the VB (i) as Sum_VB (i) and then executes an update operation. This update operation checks for TCONTs with positive VB (i), and if found, it assigns their unused bandwidth to the other TCONT (i) with negative VB (i) and that belongs to the same traffic class. This update operation equalizes the bandwidth usage among the TCONTs (i) of all ONUs (j). However, EBU uses the polling mechanism of IACG, but its polling frequency is always 1. EBU increases the polling frequency during an SI. It allocates a DBRu slot to a TCONT (i) whenever it gets an allocation during a GPA or SPA.

Fairness of allocation among multiple ONUs is an important parameter that ensures that all ONU TCONTs have an equal opportunity of getting available bytes during a GPA or SPA. GIANT does not specify any fairness mechanism. IACG and GIANT assure fairness of allocation by picking ONU TCONTs in a round-robin manner during each GPA and SPA. Another recent method to improve the fairness of DBA allocation among the ONUs using a max-min fair scheme is presented in [17]. In this technique, an ONU is allocated US bandwidth for every cycle based on its previous report or an estimated report, if the report is not available. At the end of the allocation cycle, any remaining bandwidth is allocated equally among all ONUs as in IACG. However, the study does not consider the ITU defined traffic types and does not explicitly describe the GPA and SPA phases.

Another recent study in [18] tries to improve the GIANT algorithm by executing GPA and SPA recursively, like the IACG algorithm, but the methodology is not clear and the mean delay results are very high and unacceptable. Even the mean delay for T2 traffic is around 1 s, which shows there is some flaw in their methodology.

In this study, we present an IBU algorithm that improves the scheduling mechanism of EBU and IACG and ensures priority of assured bandwidth TCONTs over best effort during an SI. IBU also proposes a novel polling mechanism for the OLT to collect the correct and latest ONU queue reports.

IV. IBU MAC ALGORITHM

In this section, we describe the scheduling and polling mechanism of IBU.

A. Polling Mechanism

IBU uses a novel polling mechanism to collect the updated queue reports from the ONUs. Figure 2 shows the DBA process execution during an SI which includes 10 XGPON cycles, from C0 to C9. The OLT sends a bandwidth allocation Gi to the ONU, which is computed in the last SI, at the beginning of C0, and allocates a DBRu slot so that the ONU sends its queue report. If the round trip time (RTT) is assumed to be equal to two XGPON frame periods, then the ONU receives Gi in C1 and sends its report R0

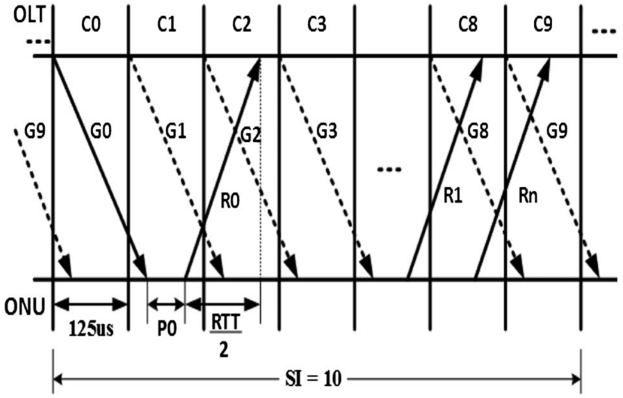


Fig. 2. ONU reporting and DBA process.

after a processing time of P_0. The OLT receives R0 near the end of C2. However, the OLT uses R0 in the next GPA and SPA at the start of C3. At this time, this report is four cycles late, as the ONU has utilized the received allocation G1, G2, G3, and G4 during C0, C1, C2, and C3. Since IACG and EBU send allocation results in every cycle in their polling mechanism, the OLT is required to subtract G0, G1, G2, and G3 from R0 before computing allocation G4. However, this holds only for RTT equal to two XGPON cycles. If RTT varies due to increase in fiber losses, then this method will fail. Therefore, IBU sends allocation results only once per SI for all the cycles in the next SI. Thus, if the same approach is used for bandwidth allocation, then the computed value of R0 will represent the ONU demand at C4 during the same SI and not for the next SI. This is because the ONU queue will further decrease after using allocations G4 to G9 during C4 to C9 before the start of the next SI.

In addition to channel delay sensitivity, the polling method of IACG and EBU also incurs extra processing load on the OLT, because remembering four values for each type of TCONT (i) requires the OLT to remember 192 values.

To compute the actual ONU demand for the next SI, we propose a different polling mechanism. In this method, an ONU subtracts the remaining unused grant of the current SI from the queue size before sending its queue report to the OLT. Thus, the received report R0 at the OLT represents the ONU demand at the end of C9. Therefore, the OLT does not require subtracting anything further from it before using it in GPA and SPA for the next SI. We explain this with an example. It is assumed that the OLT allocated 100 bytes to TCONT (i) of ONU (j) for $\mathrm{SI} = 10$. This means $\mathrm{G0}, \mathrm{G1}, \mathrm{G2}, \ldots, \mathrm{G9}$ will all be 100 bytes each. We further assume that the queue length of TCONT (i) is 1400 bytes when G0 is received. According to the method of IACG and EBU ONU, it will send $\mathrm{R0} = 1400$ bytes to the OLT, which, after subtracting G0 to G4, becomes 1000 bytes at the OLT. However, the actual demand of the ONU for the next cycle should be 400 bytes, as it already has US bandwidth allocation of 1000 bytes that will be used during this SI.

Therefore, our method provides accurate ONU demand to the OLT and does not require any further processing at the OLT to calculate the ONU's true demand. However, this method requires the ONU to use a local counter to keep track of the SI.

IBU, like EBU, increases the polling frequency during an SI by allocating a DBRu slot to ONU TCONTs more than once. However, unlike EBU, a DBRu slot is assigned to a ONU TCONT only three times when the respective SI timer has a value of 8, 5, and 2.

B. Scheduling Mechanism

IBU uses the service parameters of Table I, except in the case of the polling parameters for T4, which are as in [10,12]. In each bandwidth allocation cycle, first GPA is executed and then SPA is executed, as in IACG and EBU. Scheduling priority is for the fixed bandwidth of T1, the assured bandwidth of T2, the assured bandwidth of T3, the surplus bandwidth of T3, and finally, the surplus bandwidth of the T4 traffic class. However, in IBU, each GPA and SPA is executed for every XGPON cycle during an SI if the VB (i) for TCONT (i) is not zero and if FB is available. However, T4 TCONT's SPA should be executed only once at the end of an SI, as it is the best effort traffic class. To achieve this, IBU allows the execution of SPA for T4 only when $\mathrm{SI}_{\mathrm{min\_Timer}} = 1$. If allocation for T4 is also repeated in every SPA, as in IACG and EBU, then it may sometimes get priority over T2 and T3 in two cases. The first case is that when there is only a single report from an ONU TCONT during an SI, as in IACG. In XGPON, multiple reports can be sent simultaneously in a single DBRu field, but in GPON, only one report can be sent at a time. So, if a T4 report arrives before T2 and T3, then it can get more allocation, which results in reduced or no bandwidth allocation for T2 and T3. For example, assume that the $\mathrm{FB} = 1200$, $\mathrm{VB2}(i) = \mathrm{VB3}(i) = 400$, and $\mathrm{VB4}(i) = 1200$. So, if the queue report for T4 arrives earlier than that for T2 and T3, then T4 gets the available allocation of 1200 bytes, and, thus, FB becomes zero and no bandwidth is left behind for the T2 and T3 TCONTS in the next GPA and SPA during the same SI. This is a violation of the ITU traffic class definitions, where T4 cannot be given priority over T2 and T3 during an SI. Similarly, in a second case, where multiple reports are received from ONUs like in EBU, this problem becomes more severe. For example, assume that, if report (2), report (3), and report (4) from ONU (i) are 500, 500, and 4000 bytes, then these all arrive at the OLT during C2, and FB = 10,000 bytes. Also, assume $\mathrm{VB2}(i) = \mathrm{VB3}(i) = 4000$ bytes and $\mathrm{VB4}(i) = 6000$ bytes. Then, with the EBU algorithm during C4, the allocations assigned to T2, T3, and T4 will be 500, 500, and 4000 with remaining value of FB = 5000. Now, if new report (i) from ONU (j) arrives at C5 with report (2) = report (3) = 4000 bytes for T2 and T3 traffic, and report (4) = 1000 bytes for T4, then in this case T2 gets 4000 bytes and T3 gets only 1000 bytes due to FB becoming zero, and T4 does not get any further allocation. However, during this SI, the total allocated bandwidth to T2, T3, and T4 is 4500, 1500, and 4000 bytes with a pending demand of 3000 bytes for T3. This clearly shows violation of class priority as defined by ITU, as T4 traffic received bandwidth, while T3 demand is not fulfilled.

To ensure least priority for T4 traffic during an SI, IBU allocates to T4 only when $\mathrm{SI}_{\mathrm{min\_Timer}} = 1$. In this way, T2 and T3 get the full chance to fulfill their demand, and T4 always gets the remaining bandwidth as per the definition of the best effort traffic class. Therefore, IBU improves the mean US delays and frame loss for T2 and T3 with a slight increase in delay for T4 traffic. To compensate for this increased delay of T4, during CG, IBU allocates 36% to T4 and 32% for each T2 and T3, instead of equal assignment as in IACG and EBU. Figure 3 explains the scheduling procedure of IBU with the help of a flow chart and Figs. 4, 5, and 6 show, respectively, the pseudo-code of the IBU MAC algorithm for GPA, SPA for T3, and SPA for T4 with CG. The initial value of FB is 3888.0 bytes for a US data rate of 2.5 Gbps. All the assigned allocations are saved in a

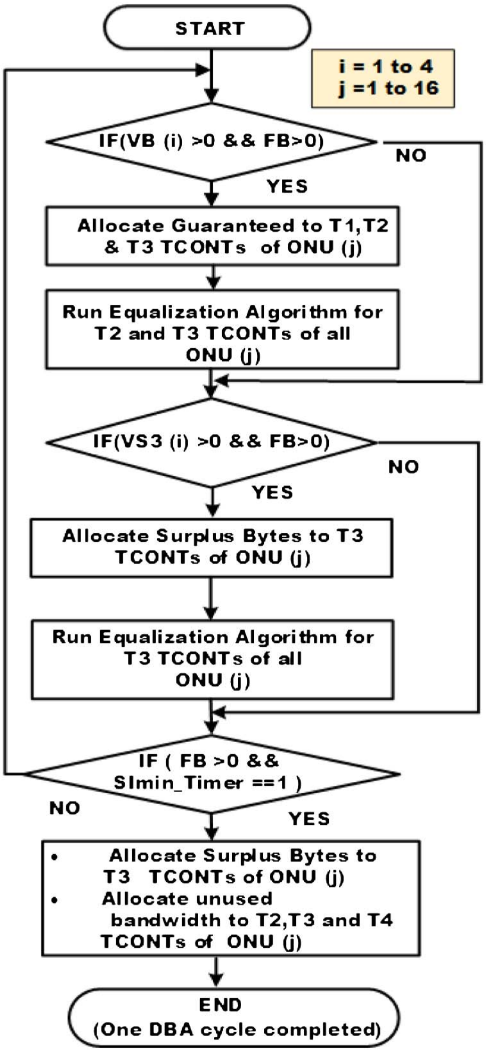


Fig. 3. IBU DBA algorithm.

bandwidth allocation array (BW [ ]), which is sent to the ONUs via a BWmap field at the end of the SI. The index of the allocation is saved in position arrays [POS (*i*)] for each TCONT (*i*), so that further allocation to TCONT (*i*) in the SPA and CG phases are added to previous allocations in the BW [ ] array.

V. Simulation Setup

An XGPON system with 16 ONUs in OMNET++ is designed with the simulation parameters shown in Table II. The queue sizes for each T1 to T4 traffic is limited to 1 MB. System performance is first evaluated by a Poisson traffic source by exponentially varying the inter-arrival time for each value of network load, as explained in [9]. Each simulation runs for 1 h and the variation of mean inter-arrival times is observed to be within a confidence interval of 95%.

```
// initially d2 = 0, n2 = b2 =16, k=0
// a = 2 or 3
 FOR (k = d2; k < n2; k + +)
 {
 r = (k % b2);
    IF ($VB_a$ [r] > 0 && FB > 0 )
   {
      ONU[r]. $Alloc_a$ =
             min($VB_a$[r], ONU [r]. $Report_a$, FB);
     ONU[r]. $Alloc_a$ =  $VB_a$ [r] ;
      $VB_a$[r]−= ONU[r]. $Report_a$ ;
      ONU[r]. $Report_a$ = ONU[r]. $Alloc_a$ ;
      FB−= ONU[r]. $Alloc_a$ ;

      IF ($First\_Time_a$ == 1 )
      {
      BW [r]. Alloc = ONU[r]. $Alloc_a$ ;
      k + +;
       $POS_a$ = k ;
       }
      ELSE
      BW [$POS_a$]. Alloc += ONU[r]. $Alloc_a$;
   }

     IF(SImax_Timer[r] == 1
    {
      SImax_Timer[r] == $SImax_a$ ;
      $VB_a$[r] = $ABmin_a$[r] ;
    }
      ELSE
      SImax_Timer[r] - - ;
 }
n2 + + ;  // For Round Robin Sequence
d2 + +  ;
```

Fig. 4. IBU pseudo code for GPA of T2 and T3.

Since IP traffic is considered self-similar in nature instead of being Poisson, the system is also analyzed with a synthetic self-similar traffic generator using 500 Pareto on–off sources, as in [5,15]. The traffic generator is designed following the method described in [19]. Each simulation runs until the total frames transmitted to each

```
// d3 = 0, n3 = b3 =16, k=0 (Initially)

 FOR (k = d3; k < n3; k + +)

{

r = (k % b3);

     IF ($VS_3$ [r] > 0 && FB > 0 )

     {

       ONU[r]. $Alloc_3$ =
              min($VS_3$[r], ONU [r]. $Report_3$, FB);
       ONU[r]. $Alloc_3$ =  $VS_3$ [r];
        $VS_3$ [r]−= ONU[r]. $Report_3$ ;
        ONU[r]. $Report_3$ = ONU[r]. $Alloc_3$;
        FB−= ONU[r]. $Alloc_3$ ;

        IF ($First\_Time_3$ == 1 )
        {
        BW [r]. Alloc = ONU[r]. $Alloc_3$;
        k + +;
        $POS_3$ = k ;
        }
        ELSE
        BW [$POS_3$]. Alloc += ONU[r]. $Alloc_3$ ;
    }

      IF(SImin_Timer[r] == 1

    {
     SImax_Timer[r] == $SImin_3$;
     $VS_3$[r] = $ABsur_3$;
    }
     ELSE
     SImin_Timer[r] - - ;
}

n3 + + ;  // For Round Robin Sequence
d3 + +  ;
```

Fig. 5. IBU pseudo code for surplus phase allocations for T3.

algorithm exceed 10^9, as in [5]. Overall in our system, the average traffic for the ONUs is balanced such that each ONU has an identical load.

```
// FB = Frame_Bytes, b4 = n4 = 16 (initially)

IF(SImin_Timer[r] == 1)

{
  FOR (k = d4; k < n4; k + +)
  {
  r = (k % b4);

      IF ($VS_4$ [r] > 0 && FB > 0 )

      {

      ONU[r]. $Alloc_4$ =

              min($VS_a$[r], ONU [r]. $Report_4$, FB);

      ONU[r]. $Alloc_4$ =  $VS_4$ [r];

      $VS_4$[r]−= ONU[r]. $Alloc_4$  ;

      ONU[r]. $Report_4$ = ONU[r]. $Alloc_4$;

       FB−= ONU[r]. $Alloc_4$ ;

     }
  }
}

   FOR (k = 0; k < j; k + +)
  {

       BW [$POS_2$ [k]]. Alloc+= $\frac{Extra\_Alloc}{j} * 0.32$

       BW [$POS_3$ [k]]. Alloc+= $\frac{Extra\_Alloc}{j} * 0.32$

       BW [$POS_4$ [k]]. Alloc+= $\frac{Extra\_Alloc}{j} * 0.36$

  }

n4 ++; // For Round Robin Sequence
d4 ++;
```

Fig. 6. IBU pseudo code for SPA for T4 and CG allocation.

Unlike all earlier DBA algorithms, T1 traffic is also considered to have a complete traffic scenario. For T1, we set $AB_{min} = 6250$ with $SI_{max} = 10$, which is equivalent to 40 Mbps. For T2 traffic, we set $AB_{min} = 1250$ with

TABLE II
SIMULATION PARAMETERS

Parameter	Details
P0	ONU frame processing time = 35 μs
ONU to OLT line rate	200 Mbps
RTT	200 μs
US and DS line rates	2.5 Gbps/10 Gbps
Mean (Poisson traffic) frame arrival rate (λ)	Varied from 96,000 frames/s to 121,600 frames/s corresponding to a load variation from 0.1 to 1.7
Frame size	Chosen from a triangular distribution with 60%, 20%, and 20% probability of 64, 500, and 1500 bytes, respectively, as in [10,12].
E[ON]	Mean length of ON periods of individual Pareto sources in bytes. Taken as 12,000 bytes.
E[OFF]	Mean length of OFF periods of individual Pareto sources in bytes = $\frac{1}{L_{\text{Pareto}}} - 1$
$a_{\text{ON}}, a_{\text{OFF}}$	Pareto shape parameter with ON and OFF values of 1.4 and 1.2, respectively.
$b_{\text{ON}}, b_{\text{OFF}}$	Pareto location parameter with ON value = 335.5 and OFF value = $(b_{\text{ON}})(0.597)(\frac{1}{L_{\text{Pareto}}} - 1)$
L_{Pareto}	Load of multiplexed Pareto stream varied from 0.1 to 0.99. Corresponds to a network load variation of 0.1 to 1.7

$\text{SI}_{\max} = 10$, which is equal to 80 Mbps. For T3 traffic, we set $\text{AB}_{\min} = \text{AB}_{\text{sur}} = 6250$ with $\text{SI}_{\max} = \text{SI}_{\min} = 10$, which means 40 Mbps is given to both the assured bandwidth and the non-assured bandwidth. For T4 traffic, we set $\text{AB}_{\text{sur}} = 15,624$ and $\text{SI}_{\max} = 10$, which is equivalent to 100 Mbps.

VI. RESULTS

The mean delays, frame loss ratio, and unallocated bandwidth ratio results for T1, T2, T3, and T4 traffic for both types of traffic source are illustrated in Figs. 7 and 8, respectively. The variation of traffic load from 0.1 to 1.7 corresponds to a per ONU data rate of 20 to 265 Mbps. In the case of a Poisson traffic source, an increase in load results in more traffic frame arrivals per ONU and, thus, more queuing delays and increased chance of frame loss for T3 and T4 traffic due to lesser priority and limited buffer availability at the ONU. For a self-similar traffic source, an increase in load results in longer ON periods of multiplexed traffic stream. However, each ONU has a separate traffic source and, thus, if the traffic generator of some ONUs has an ON period, others might have OFF periods. We call this the split load condition. Because of this behavior, mean delays of all traffic types do not increase sharply as load increases, as in the case of a Poisson traffic source. The results also indicate a lot of variations. Even frame loss occurs at quite lower loads due to the sudden arrival of a longer traffic burst. In both cases, IBU shows lower mean

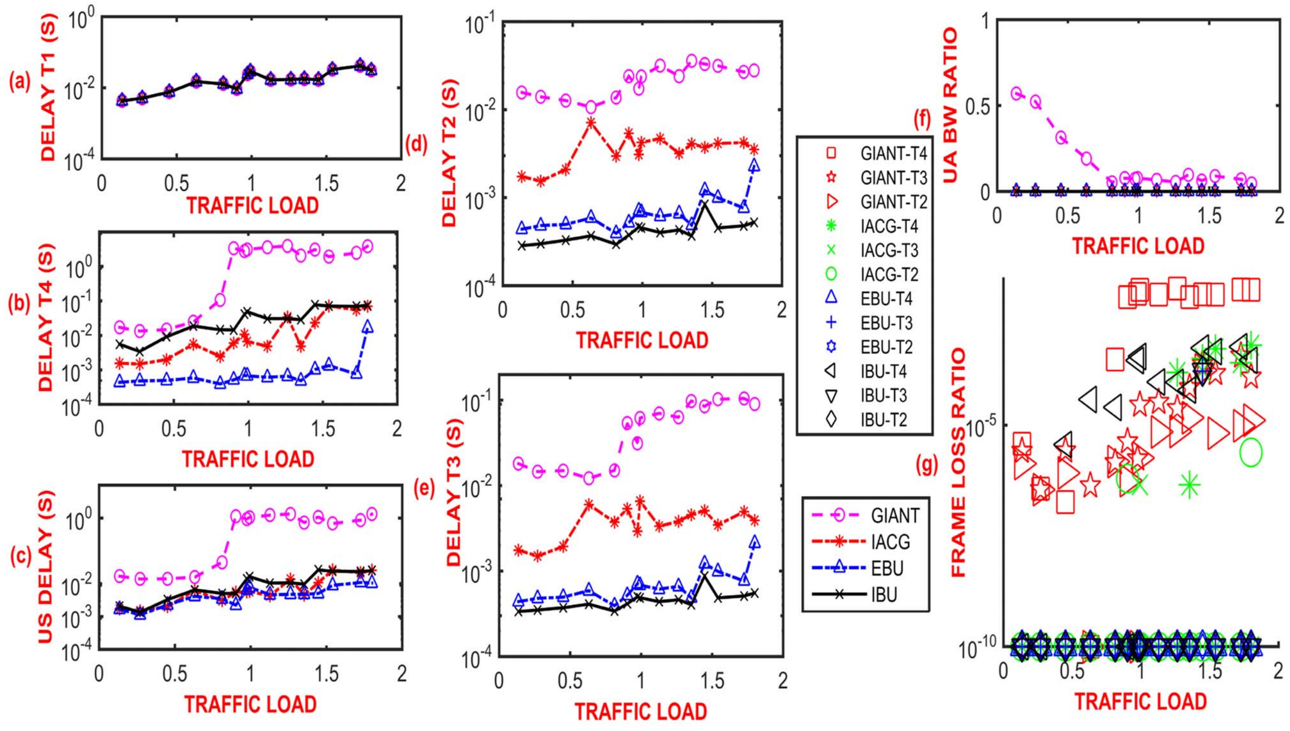


Fig. 7. IBU performance results with self-similar traffic source. (a) Mean delay T1, (b) mean delay T4, (c) mean US delay, (d) mean delay T2, (e) mean delay T3, (f) unallocated bandwidth ratio, and (g) frame loss ratio.

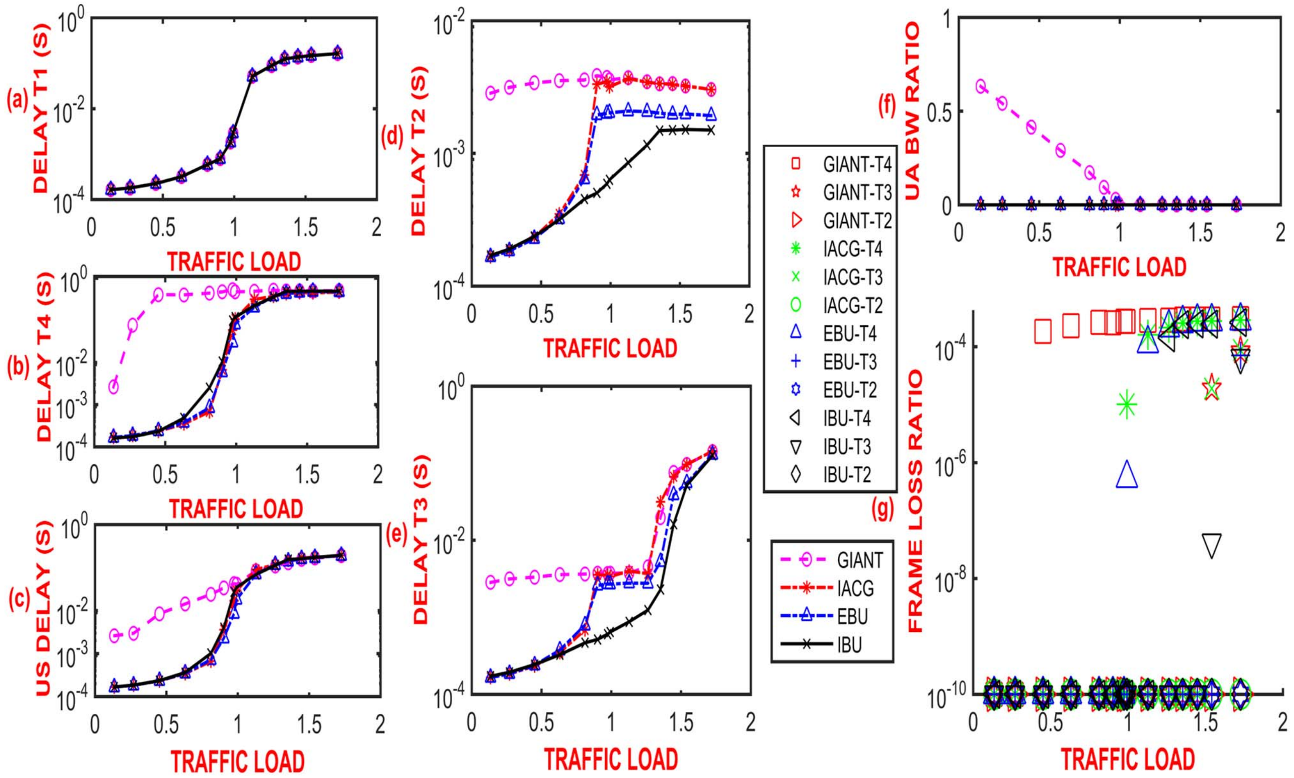


Fig. 8. IBU performance results with a Poisson traffic source. (a) Mean delay T1, (b) mean delay T4, (c) mean US delay, (d) mean delay T2, (e) mean delay T3, (f) unallocated bandwidth ratio, and (g) frame loss ratio.

delays for both T2 and T3 traffic and the fewest frame losses compared to all other algorithms. For T4, the traffic performance of IBU is relatively poor compared to IACG and EBU due to strictly ensuring priority of T2 and T3 over the T4 traffic class.

The performance of the T1 traffic class as shown in Figs. 7(a) and 8(a) is observed to be same for all algorithms as it utilizes a fixed allocation. As the load increases beyond 0.2, corresponding to around 50 Mbps of traffic arrival rate, the mean delay of T1 rises exponentially because of fixed bandwidth allocation of only 40 Mbps.

T2 traffic shows the least delay due to assured bandwidth assignment. In the case of a Poisson traffic source for IACG and EBU, delay is initially lesser due to CG allocation, but, as CG is unavailable at around 0.8 load, it becomes constant and only T2 enjoys a constant delay even at loads higher than 1.6. IACG starts following GIANT as its CG is not available. EBU performs better than IACG because of its higher queue reporting frequency and equalization process. However, IBU again surpasses all others due to the improved scheduling mechanism. Compared to GIANT, IBU improves mean delay of T2 around 94% at a load 0.5 and around 85% at load around 1. Compared to IACG, delay improves from 9% to 80%, and from 1.2% to a maximum of 70% compared to EBU as load increases beyond 0.5. When the load is less than 0.5, IACG, EBU, and IBU show almost the same performance due to CG. However, in the case of a self-similar traffic source, the mean delay of T2 traffic remains almost constant with some variations due to the split load condition, which results in CG availability at almost all loads. Since GIANT does not use CG, it shows the highest delay at all loads. IBU shows an improvement of 96% to 98.7% versus GIANT, 80% to 94% versus IACG, and 24% to 76% versus EBU in mean delay of T2 traffic.

The performance of the T3 traffic class with a self-similar traffic source follows almost the same pattern as that of T2 for all the algorithms. However, due to the 50% surplus bandwidth part, its delay slightly increases. Overall, IBU shows an improvement of 96.6% to 99.5% versus GIANT, 76% to 93% versus IACG, and 13% to 73% versus EBU in mean delay of T3 traffic. With the Poisson traffic source, the behavior of T3 traffic is different from that of T2 traffic. GIANT shows higher delay until a load of 0.7 due to not using CG. After that, it starts following IACG and shows almost constant delay until the load reaches 1.3. At this point, the frame arrival rate reaches 3.2 Gbps (16 ONUs each of 200 Mbps sum to 3.2 Gbps) and T3 starts losing its surplus portion allocation; then at load around 1.4, it also starts losing its assured allocation. This results in an exponential rise of delay. EBU shows lower delays compared to both GIANT and IACG due to the higher ONU queue reporting frequency and equalization process. IBU again performs better than other algorithms, and compared to GIANT, it shows 94% less delay at a load of 0.5 and around 80% better at a load of 1.

Compared to IACG, it improves from 6% to a maximum of 90%. Versus EBU, it shows an improvement minimum of 12% to a maximum of 70% as load increases beyond 0.5.

T4 traffic is best effort traffic and thus shows higher delays compared to T2 and T3 traffic, as shown in Figs. 7(d) and 8(d), respectively. With the Poisson traffic source, as the load reaches 1, the cumulative network traffic rate reaches 2.5 Gbps, which is the maximum capacity for an XGPON upstream link. Therefore, from this point onward, T4 does not get any allocation and its delay starts rising exponentially. Since, in simulation for measuring the upstream delay, it is necessary that the traffic frames from the ONU reach the OLT, we assign a minimum of 1 byte allocation to T4. Therefore, after exponentially rising, T4 delay becomes nearly constant. This is due only to our inability to measure this exponential rise as all T4 TCONTs are unable to reach the OLT in the simulation setup. Otherwise, it should rise exponentially toward infinity. In the case of a self-similar traffic source, delay is higher compared to the T2 and T3 traffic classes, but it does not sharply increase due to the split load condition. GIANT shows the highest delay values for the T4 class with both traffic sources. Both EBU and IACG show lesser mean delay for T4 because priority order of traffic classes is not maintained. This is more visible with a self-similar traffic source than that due to split load, mostly because there is availability of surplus bandwidth. This leads to the T4 traffic class getting priority over T2 and T3, as discussed in Subsection IV.B. However, increased delays for T4 traffic in IBU is not a disadvantage as, by definition, the best effort traffic should be served with whatever is left after serving higher priority traffic classes. The lower delay values of IACG and EBU compared to IBU also prove that there is a violation of priority order in both of these algorithms that is rectified by IBU.

Due to a limited buffer of 1 MB at the ONU, frame loss occurs for the T1, T3, and T4 traffic classes as illustrated in Figs. 7(g) and 8(g). The highest frame loss ratios are for the T4, T3, and T2 traffic classes of GIANT, followed by the T4 traffic class of IACG. Minor frame losses are also observed for other traffic classes, which shows that a 1 MB buffer for a traffic class at the ONU is not sufficient with XGPON. The unallocated bandwidth ratio decreases with increase in load for GIANT, while it is always zero for IACG, EBU, and IBU due to utilizing CG, as presented in Figs. 7(f) and 8(f).

VII. CONCLUSION

In this study, we have presented IBU, which is an ITU-complaint DBA algorithm. It improves the GIANT, IACG, and EBU algorithms by modifying the polling and scheduling mechanisms of IACG and EBU. The polling mechanisms of IACG and EBU do not report the true ONU bandwidth demand during an SI. It is also sensitive to channel delay. Their scheduling mechanisms do not strictly ensure traffic class priority and give preference to best effort traffic over the assured traffic. IBU uses a novel polling mechanism to report the correct and updated ONU demand to the OLT. IBU achieves this by delaying the allocation to T4 traffic until the respective SI timer = 1. It outperforms all the existing algorithms in terms of mean delay and frame loss for the T2 and T3 traffic, but the delay for T4 increases, which shows that, in other algorithms, the T4 traffic class was getting priority over T3 and T2 traffic, resulting in lower delays of T4 traffic but increased delays for T2 and T3. In the future, we will study the impact of DBA performance on cyclic sleep in an XGPON-based network.

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REFERENCES

[1] Y. Luo and J. Bu, “How valuable is information and communication technology? A study of emerging economy enterprises,” *J. World Business*, vol. 51, pp. 200–211, 2016.

[2] B. Sanou, ICT Facts and Figures. The World in 2015, ITU Telecommunication Development Bureau 2015 Report, Geneva, Switzerland, May 2015 [Online]. Available: https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2015.pdf.

[3] M. Hadi and M. R. Pakravan, “Analysis and design of adaptive OCDMA passive optical networks,” arXiv:1607.07707, 2016.

[4] J.-Y. Monfort, “Basic requirements to quality of service (IP centric),” in *Workshop on Standardization in E-Health*, 2003.

[5] M.-S. Han, H. Yoo, B.-Y. Yoon, B. Kim, and J.-S. Koh, “Efficient dynamic bandwidth allocation for FSAN-compliant GPON,” *J. Opt. Netw.*, vol. 7, pp. 783–795, 2008.

[6] “10-gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification,” ITU-T Recommendation G.987.3, Oct. 2010.

[7] “Gigabit-capable passive optical networks (GPON): General characteristics,” ITU-T Recommendation G.984.1, Mar. 2008.

[8] IEEE 802.3ah Task Force [Online]. Available: http://www.ieee802.org/3/efm.

[9] S. Hussain and X. Fernando, “EPON: An extensive review for up-to-date dynamic bandwidth allocation schemes,” in *Canadian Conf. on Electrical and Computer Engineering (CCECE)*, 2008, pp. 511–516.

[10] N. M. Din, N. A. M. Radzi, S. K. Sadon, and M. H. Al-Mansoori, “Approaches in dynamic bandwidth allocation in passive optical network systems,” in *IEEE 4th Int. Conf. on Photonics (ICP)*, 2013, pp. 10–14.

[11] K. Kanonakis and I. Tomkos, “Offset-based scheduling with flexible intervals for evolving GPON networks,” *J. Lightwave Technol.*, vol. 27, pp. 3259–3268, 2009.

[12] J. D. Angelopoulos, H.-C. Leligou, T. Argyriou, S. Zontos, E. Ringoot, and T. Van Caenegem, “Efficient transport of packets with QoS in an FSAN-aligned GPON,” *IEEE Commun. Mag.*, vol. 42, no. 2, pp. 92–98, 2004.

[13] H.-C. Leligou, C. Linardakis, K. Kanonakis, J. D. Angelopoulos, and T. Orphanoudakis, “Efficient medium arbitration of FSAN-compliant GPONs,” *Int. J. Commun. Syst.*, vol. 19, pp. 603–617, 2006.

[14] M.-S. Han, “Simple and feasible dynamic bandwidth and polling allocation for XGPON,” in *16th Int. Conf. on Advanced Communication Technology (ICACT)*, 2014, pp. 298–304.

[15] M. S. Han, H. Yoo, and D. S. Lee, “Development of efficient dynamic bandwidth allocation algorithm for XGPON,” *ETRI J.*, vol. 35, pp. 18–26, 2013.

[16] M. Feknous, A. Gravey, B. Le Guyader, and S. Gosselin, “Status reporting versus non status reporting dynamic bandwidth allocation,” in *6th Int. Conf. on the Network of the Future (NOF)*, 2015, pp. 1–7.

[17] I. Gravalos, K. Yiannopoulos, G. Papadimitriou, and E. Varvarigos, “The max-min fair approach on dynamic bandwidth allocation for XG-PONs,” *Trans. Emerging Telecommun. Technol.*, vol. 26, pp. 1212–1224, 2015.

[18] J. A. Arokkiam, K. N. Brown, and C. J. Sreenan, “Refining the GIANT dynamic bandwidth allocation mechanism for XG-PON,” in *IEEE Int. Conf. on Communication (ICC)*, 2015, pp. 1006–1011.

[19] G. Kramer, *Ethernet Passive Optical Networks*. New York: McGraw-Hill, 2005.

Rizwan Aslam Butt is pursuing his Ph.D. in the area of passive optical networks at the University of Technology Malaysia in the Electrical Engineering Department. He is also a Lecturer at NED University of Engineering and Technology (NED UET), Pakistan. He has also worked as an Engineer for four years with Pakistan Telecommunication Company. He obtained his bachelor’s degree in electronics, master’s degree in computer science, and master’s degree in telecom engineering from NED UET. His research interests include optical and communication networks.

Sevia Mahdliza Idrus is a Professor and faculty member of the Electrical Engineering Department of the University of Technology Malaysia (UTM). She received her bachelor’s degree in electrical engineering and master’s degree in engineering management both from UTM in 1998 and 1999, respectively. She obtained her Ph. D. in 2004 from the University of Warwick, UK, in optical communication engineering. Her main research interests are optical communication systems, communication networks, and IoT. Her research output has been translated into a number of publications and intellectual properties, including a high-end reference book, *Optical Wireless Communication: IR Connectivity*, published by Taylor and Francis; 5 books published by Pearson, Springer, and Novar; 49 book chapters and monographs; over 150 technical papers; 4 granted patents; 35 patent filings; and 28 UTM copyrights. She is actively involved in international collaboration projects. She has been invited as a guest speaker at a number of international conferences. She was invited as a Guest Professor at Osaka Prefecture University and Tokai University in Japan in 2011 and 2014, respectively.

Kashif Naseer Qureshi has received his Ph.D. from the Department of Computer Systems and Communications of the University of Technology Malaysia (UTM), his master’s degree in information technology in 2012 from IM Sciences Peshawar Pakistan, and his master’s degree in computer science in 2003 from Baluchistan University Pakistan. He is a Cisco Certified Network Professional (CCNA-CCNP) and is Microsoft (MCSE, MCITP) certified. He is an active reviewer for various reputable academic journals. He has authored 39 Scopus and 10 ISI indexed journal articles.

Nadiatulhuda Zulkifli is a Senior Lecturer in the Department of Communication Engineering, Faculty of Electrical Engineering, University of Technology Malaysia (UTM). She obtained a bachelor’s degree in electrical telecommunication from UTM and received her master’s degree and Ph.D. from the University of Essex, UK. She has authored a number of international journal and peer-reviewed conference papers. Her research interests cover optical communication and networking, mobile commerce, and innovation adoption.

Siti Hasunah Mohammad is a Ph.D. student at the University of Technology Malaysia. She received her B.Eng. degree in electrical–telecommunication in September 2010 and her M.Eng. degree in electrical in September 2013 from the University of Technology Malaysia, Johor Bahru, Malaysia. Currently she is working toward a Ph.D. in the Faculty of Electrical Engineering at the University of Technology Malaysia. Her current research interests include quality of service in optical networks and heterogeneous optical wireless networks.