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A Novel Scheduling and Polling Mechanism for Upstream Bandwidth Assignment in A Passive Optical Network

R. A. Butt[1], M. Y. Anwar[2], M. W. Ashraf[3], M. Z. Arfeen[4]

[1]Telecom Engineering Department, NED University of Engineering and Technology, Karachi, Pakistan
[2,3]Computer Engineering Department, BanhuddinZakariya University, Multan, Pakistan
[4] Electronics Engineering Department, Bahria University, and Karachi, Pakistan
[1]rizwan.aslam@neduet.edu.pk

Abstract-In a dynamic bandwidth assignment (DBA) scheme for a passive optical networks (PON), a polling mechanism with higher polling frequency helps OLT to accurately enquire the ONU upstream bandwidth demand. However, due to channel delay, an increase in polling frequency leads to inaccurate bandwidth reporting as the queue reports reach OLT after some delay. This results in inefficient bandwidth reporting (IBR) problem. This IBR problem causes wastage of upstream bandwidth due to inaccurate bandwidth assignment and also leads to higher upstream delays at high traffic loads. This study presents a novel polling and scheduling mechanism which eliminates the IBR problem. In this scheduling mechanism the OLT sends bandwidth allocation for the whole SI period to a TCONT (*i*) of ONU (*i*) at once instead of sending it in every downstream frame. A novel polling mechanism is also presented that subtracts the future grants from the queue reports at the ONUs before sending them to the OLT to combat the channel delay impact. The results obtained through the simulation study show that the proposed scheme improves mean upstream delay by 62% for type 2, 3 and 4 traffic classes compared to EBU and up to 99% compared to IACG DBA scheme.

Keywords-Dynamic Bandwidth Assignment, DBA, Passive Optical Network, Polling Mechanism

I. INTRODUCTION

Due to the exponential growth in cellular mobile subscriptions, growing internet usage for online video streaming services like Netflix, video conferencing and cloud computing trends, the bandwidth requirements are continuously increasing [i]. A recent report of ITU [ii] has reported that 53.6% of the population of the world is using Internet at their homes and specifically the in developed countries this ratio is even higher and today 84.4% of the world population has access to the internet. Due to this widespread Internet use, the demand for the high speed broadband services is continuously increasing. For providing such services, the passive optical network (PON) has emerged s the most sustainable and cost-effective option as it offers high bandwidth, very long reach and easier deployment. It also has relatively lower operating and maintenance costs due to being passive in nature in the outside plant (OSP) [iii]. The PON technologies such as EPON and GPON offer a capacity of 1 and 2.5 Gigabit per second (Gbps) with a split ratio of 32 to 64. These PON use a wavelength of 1490nm for downstream and a dedicated 1310nmwavelength for upstream on the same optical fiber. Their upgraded versions GEPON and XGPON offer increased capacity up to 10Gbps with a higher split ratio of 64-128 [iv]. The downstream traffic pattern of these PONs is broadcast and every Optical Network Unit (ONU) extracts its related information from the received frames and discards rest of the frame. However, in the upstream direction simultaneous communication from all the ONUs is not possible as the transmission is on the same wavelength [iv]. A bandwidth management mechanism is, therefore, necessary to efficiently distribute upstream bandwidth fairly to all the ONUs.

A simple arbitration mechanism like fixed timeslot assignments to each ONUs is highly inefficient as it cannot assign extra bandwidth to an ONU requiring more bandwidth due to higher traffic load. This also results in higher upstream delays for such ONUs as their traffic queues start increasing due to limited bandwidth availability. Another clear disadvantage is the wastage of unused bandwidth by the ONUs with lower traffic loads. Therefore, by using a dynamic bandwidth distribution mechanism the wasted bandwidth of the under load ONUs can be assigned to the ONUs with higher traffic load. Such a scheme also has the advantage that it can assign bandwidth to multiple traffic classes inside an ONU with different bandwidth requirements. Moreover, a dynamic bandwidth assignment (DBA) mechanism also helps the service providers to increase their revenue by allowing more subscription higher than the available system capacity, on best effort basis, andstill guaranteeing the quality of service (QoS) in compliance to the agreed service level agreements (SLAs).

A PON network has to support multiple types of broadband services like video conferencing, leased lines and VoIP in addition to basic voice and video services. ITU categorizes PON traffic in four different traffic classes; T1, T2, T3 and T4 [v], [vi] and the IEEE PONs use there traffic classes; expedited forward (EF), assured forward (AF) and best effort (BE) traffic classes defined by IETF [vii]. The delay bounds and bandwidth requirements of each of these services are different. Therefore, the need for an efficient DBA at OLT becomes critically important. A DBA uses Alloc_IDs to discriminate between dissimilar traffic types and assign bandwidth to each queue as per its bandwidth requirement and the SLA [viii], [ix].

The commercially deployed PON standards of both IEEE and ITU ([viii-x]) do not stipulate any specific DBA scheme and leave its implementation to the vendor. Therefore, this area has drawn attention of the researchers and many studies have been conducted on an efficient DBA design for PON. Particularly, EPON DBA has got most of the attention as it does not have strict bandwidth requirements forits traffic classes. Moreover, the simulation design process for EPON is easier as it is based on Ethernet standard for which simulation models are easily available. On the other hand for ITU PONs no simulation models are available and they require extensive efforts for a simulation design due to their complex MAC layer. To the best of our knowledge, existing research works on DBA largely focus on EPON technology whereas very limited studies [ix], [xi][xvii] have considered GPON / XGPON DBA due the same reasons discussed above.

Every ITU compliant DBA scheme comprises of a polling and a scheduling process. The existing DBA schemes for the ITU compliant PONs use mainly two types of polling and scheduling approaches; polling each TCONT (i) and scheduling bandwidth grants only once during a service interval (SI) [v], [ix], [xii], [xviii], or polling every TCONT (i) and schedule grants every downstream cycle. Where, a transmission container (TCONT) is a virtual traffic container that represents a specific traffic class with i = 1,2,3,4. The first DBA approach results in inaccurate traffic demand reporting and thus inefficient assignment of bandwidth which leads to higher US delays and frame losses. The latter approach improves these weakness for low traffic loads but it suffers from inefficient bandwidth reporting (IBR) problem which causes wastage of upstream bandwidth and, thus, higher upstream delays at high traffic loads. To overcome this problem, this study presents a novel polling mechanism in which the ONUs are polled only once during an SI but the bandwidth grants are scheduled for the whole SI period in a single BW map of the DS frame instead of scheduling it every DS frame.

The rest of the paper is structured as: Section-II reviews the related work, the target PON system is defined in Section-III, Section-IV presents and explains the proposed scheme, Section-V describes the simulation setup, section VI presents and discusses the results. Finally, Section-VII concludes the paper with future research direction.

II. RELATED WORK

IPACT [xixs], [xx] is among the pioneer DBA scheme presented for EPON. Its basic version followed an online approach in which the OLT has to wait for all the ONU queue reports. The problem with DBA algorithms following this approach is of fairness. They do not assign bandwidth grants to all the ONUs with fairness as OLT does not wait for all the queue reports. This may also lead to monopolization of channel by the overloaded ONUs. Therefore, another variation of IPACT is offline mode or IPACT with stop[xxi]which has been studied in [xxiis], [xxiii] . In such schemes the OLT waits for all the queue reports and then executes the DBA algorithm. Due to the availability of all the queue reports with OLT, it can easily and fairly assign bandwidth fairly to all the TCONTs. However, this approach creates idle channel problem due to increase in OLT waiting for the ONU reports. This problem has been addressed by online-offline hybrid DBA approaches[xxii], [xxiv-xxvi]. These schemes classify ONUs in two sub-groups and allocate bandwidth in an online manner to one group and in an offline manner to the other, keeping in view their bandwidth demand according to their traffic load. An review of the EPON compliant DBA schemes have been presented in [xxii], [xxvii]. However, ITU PONs, unlike EPON, are synchronous in nature and the DBA schemes for EPON are not feasible for these PONs.

Inspired from the idea of IPACT, a similar DBA algorithm for GPON was presented in [xvi] but the scheduling and polling mechanisms were not revealed. Many DBA schemes [xxviii-xxx] have been proposed for PON and these can be classified based on their polling and scheduling processes.

The job of the polling process is to fetch the correct ONU traffic demand at the OLT so that it can execute the DBA process and schedule the bandwidth grants accordingly. From, the polling perspective, the DBA schemes can be classified as; Fixed polling (FIP), Iterative polling (ITP) and the Hybrid polling (HYP). In the FIP approach, the ONUs are polled for their queue reports only once during an SI. The GIANT [ix], [xii], [xviii], IACG [xiii], [xiv], and GREAL [xxxi] are examples of such DBA schemes. An iterative polling approach improves the US delays by reducing the waiting time of the newly arrived frames at the ONU. EBU [xv], [xxxii] and BUDA [xxiii] schemes are an example of such DBAs which poll each TCONT (i) whenever a grant is scheduled for it. However, this approach wastes significant bandwidth as each polling slot consumes 4 bytes in the upstream frame. Therefore, hybrid polling approach is a better option that provides updated queue reports with lesser bandwidth wastage in polling slots. IBU[xxxiv], CBA-LR [xxviii] and CBU [xvii] are examples of such DBAs. Table I shows the merits and demerits these polling mechanisms.

In addition to the polling mechanism, the scheduling mechanism also plays very important role in the reduction of the upstream delays. The scheduling mechanism for ITU PONs can be classified with respect to bandwidth assignment as fixed assign (FAS), iterative assign (IAS), excess assign (EAS) and unused assign (UAS). The FAS schemes schedule a bandwidth grant only once during an SI e.g. the GIANT DBA. These schemes suffer from higher upstream delays and lead to idle channel problem. The IAS approach reduces the channel idle time and improves the upstream delays by scheduling the bandwidth grants every DS cycle and sending through the BWmap field of DS frame. The example of IASDBA are EBU, GREAL, CBA-LR and CBU schemes. However, the IASschemes alone cannot fully utilize the upstream bandwidth. Thus, EASschemes integrated with IAS schemes are highly efficient in minimizing the upstream delays and channel idle time. EBU, CBU and EBA-LR are examples of such DBAs. However, the IAS DBA schemes when used with an ITP approach suffer from IBR problem. This happens due to channel delay because the queue reports reach after a delay of downstream cycles at OLT during which time OLT has already scheduled some grants. To fix this problem the authors of IACG and EBU schemes propose subtraction of a fixed number of assigned grants from the received queue reports. However, if the excess bandwidth is not completely assigned at the OLT then it is actually not aware of grants assigned that should be subtracted from the received queue reports. The CBA-LR and CBU schemes solve this problem with an improved EAS mechanism in which the excess bandwidth is assigned completely at the OLT to each TCONT (*i*). EBU also utilizes the UAS scheme in addition to EAS and ITP schemes to further improve the upstream performance but its UAS algorithm leads to degraded performance of lower priority traffic classes. The CBU scheme improves the UAS algorithm of EBU. However, its methodology is computationally expensive and quite complex. A summary of the merits and demerits of the scheduling mechanisms is shown in Table I.

In this study, another simpler and novel polling mechanism is proposed which we term as comprehensive bandwidth assignment (CBA). It is an integration of FIP and ITPschemes and combines the advantages of both approaches and eliminates the IBR problem. In this approach like FIP the grants are scheduled only once but the grants are scheduled for the whole SI period and thus it becomes analogous to ITP approach. However, it is different from the HYP approach as the grants are sent only once in an SI

TABLE I
MERITS AND DEMERITS OF THE POLLING AND SCHEDULING MECHANISM FOR ITU COMPLIANT PONs

Scheme	Objective	Merits / Demerits
Fixed Polling (FIP)	•OLT polls each TCONT (*i*) of ONU (*i*) only once during an SI.	•Wastes minimum bandwidth in polling process. •Causes higher waiting time for the newly arrived frames before they get reported to the OLT.
Iterative Polling (ITP)	•OLT polls each TCONT (*i*) of ONU (*i*) every DS cycle.	•Wastes maximum bandwidth in polling process. •Causes minimum waiting time for the newly arrived frames and they get immediately reported to the OLT.
Hybrid Polling (HYP)	•OLT polls each TCONT (*i*) more than once during an SI but not every DS cycle.	•A middle approach which reduces polling bandwidth as well as the waiting time of the newly arrived frames.
Fixed Assign (FAS)	•OLT tries to schedules US grant for a TCONT (*i*) only once during an SI.	•Leads to higher channel idle time and does not fully utilize US channel and thus causes higher US delays for all the TCONT (*i*).
Iterative Assign (IAS)	•OLT tries to schedules US grant for a TCONT (*i*) every US cycle during an SI.	•Minimizes channel idle time and tries to fully utilize the US bandwidth and thus minimizes the US delays for all the TCONT (*i*).
Unused Assign (UAS)	•OLT tries to schedule additional unused grant of under-load TCONTs (*i*) to the overloaded TCONT (*i*) belonging to same traffic class.	•Reduces delays for the higher priority TCONT (*i*) but leads to increased delays of best effort TCONT (*i*) due to availability of reduced bandwidth due to over assignment to higher priority traffic classes.
Excess Assign (EAS)	•OLT tries to schedule additional grant to a TCONT (*i*) if there is unassigned bandwidth found at the end of a DBA cycle.	•Helps to reduce US delays of all the TCONT (*i*). •Leads to higher bandwidth waste per US cycle at the ONU at low traffic loads.

period. Further, the grants scheduling is done in a round robin manner for fairness. The received allocations are used by the ONUs in the future cycles of the current SI. However, this method requires slight modification in the BW map field as for an SI = 10 and with four Alloc-IDs per ONU and for a total of 16 ONUs there will be a requirement of 640 allocation entries in the BWmap but the current standard limits it to 512. However, this change is minimal and do not require any physical layer changes in the ONU architecture. The CBA scheme also improves the RBW algorithm of IACG and EBU schemes and divides the excess bandwidth in a weighted manner in proportion to the queue reports of a TCONT (*i*) instead of an equal assignment.

III. System Description

This section explains the PON system considered for this study. Generally, a PON system has 16 to 64 ONUs, all connected to an OLT port through branches of an optical fiber network. It uses a power splitter to passively split the optical light to different fiber branches. This study assumes an ITU compliant PON which uses a specific frame structure termed as generic encapsulation module (GEM) to carry multiple traffic frames simultaneously. It is a synchronous network in which both OLT and ONU communicate in a synchronized manner [xxxv] and send their frames at a frequency of 8 KHz. Each GEM field attaches a special header to each payload unit and identifies it uniquely with the help of a Port-ID. The payload length indicator (PLI) field helps in the frame fragmentation. Multiple GEM sets are associated with a TCONT that is identified by an Alloc-ID. Both the PTI and Port-ID fields help the OLT to reassemble the traffic frames arriving from an ONU. To ensure data integrity of the payload, a header error control (HEC) is used for error detection.

For a DBA scheme to assign bandwidth to an ONU, it is necessary to have the knowledge of the traffic demand of the ONU traffic classes. This can be done in two ways; Non Status Reporting (NSR) and Status Reporting (SR) [xxxvi], [xxvii]. In NSR approach the OLT does not ask the ONUs for their traffic demand and itself estimates bandwidth requirements from the traffic arrival rate of the ONUs. In the second approach, the OLT requests ONUs to send their bandwidth demand in the form of their queue reports for all the traffic classes. These reports are sent to OLT using the Dynamic Bandwidth Report (DBRu) field of the upstream frame. This study uses a SR based approach. The disadvantage of this approach is that it requires 4 bytes if mode 1 is used or 2 bytes if mode 2is used for the sending the queue report of TCONT (*i*) in the upstream frame. The DBA scheme assigns bandwidth to ONUs to engage the upstream media for this time to transmit traffic to OLT. The ITU PONs allocate this time in terms of a number of bytes to the TCONT (*i*) of an ONU (*i*) according to the nature of the traffic and the ONU bandwidth demand indicated by the ONU buffer occupancy reports. Whether the DBA process executes every downstream cycle or only once during an SI at the OLT, the bandwidth assignment to a TCONT (*i*) remains fixed for the period of SI in both cases. Every DBA cycle consists of an assured bandwidth assignment phase during which a minimum bandwidth in bytes termed as AB_{min} is allocated to T1, T2 and T3 TCONTs. Then, in surplus phase, additional bandwidth (AB_{sur}) is assigned to T3 and T4 on need cum availability basis. However, the bandwidth assignment to T1 is always fixed and do not require queue report.

The upstream capacity of XGPON in bytes is 38880 bytes and is termed as frame bytes (FB) and should satisfy Equation (1). Ideally, the sum of the CIR and PIR should be less than FB so that there is some bandwidth availability for the best effort traffic class even at higher traffic loads [x]. Upstream frame delay (D_{US}) depends upon four factors as given by Equation (2), where Q_D is the waiting time of the frame in the queue before it gets the upstream bandwidth. P_D is the processing delay incurred in bandwidth assignment by the OLT. T_D is the upstream channel delay which is typically half of the round-trip time (RTT). T_{Poll}, is the time which OLT takes in sending the bandwidth allocation periodically to ONUs. Except Q_D, the other factors remain constant, however, the Q_D increases with the increase in traffic load because this leads to an imbalance in the ratio of service rate and the traffic arrival rate as a higher arrival rate leads to increase in traffic queuing. The T_{Poll} depends on the polling frequency of the DBA process and is typically constant for a particular DBA scheme. Therefore, the D_{US} exclusively depends upon the proficiency of the DBA algorithm as well as the traffic arrival rate of the US traffic. The guaranteed service rate is defined as $\frac{AB_{min}}{SI_{max}}$ and the surplus rate as; $\frac{AB_{sur}}{SI_{min}}$. Table II defines the mportant parameters for the rest of paper.

$$PIR + CIR \leq FB \quad (1)$$

$$D_{US} = Q_D + P_D + T_D + T_{Poll} \quad (2)$$

IV. Proposed DBA Mechanism

A. Polling Mechanism

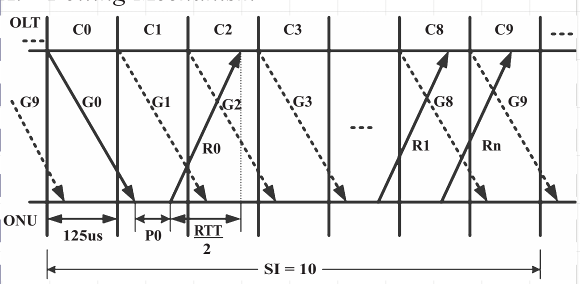

Fig. 1. ONU polling process for the collection of queue reports

CBA scheme introduces a mechanism for polling TCONTs of all ONUs to get their queue reports at the OLT. This mechanism is explained with the help of Fig.1 which shows the polling process with C0, C1, C2….C9 XGPON cycles for an SI = 10. OLT sends bandwidth allocation G0 computed in previous SI to ONUs at the start of C0 and also allocates DBRu slot to send their Queue Reports. The ONU uses the G0 for the whole SI without looking into the downstream BWmap fields and G1, G2, G3, G4, G5, G6, G7, G8 and G9 act as virtual grants. ONU also uses local SI counter to keep count of the SI and the remaining grants for the current SI. If RTT =200us, then an ONU receives Gi in C1 and takes a processing time P0 to send its report R0 to OLT which is received by the OLT will at the end of C2. Therefore, OLT will actually be able to use the R0 for the next GPA and SPA phases in the next cycle C3. However, by this, this queue report will not be accurate as four US cycles will have already passed during which the ONU would have utilized the received allocation Gi. Thus, to obtain the actual demand of ONU IACG and EBU suggests subtracting G0, G1, G2 and G3 from R0 before using it in next bandwidth allocation cycle. Since IBU sends allocation for all the cycles till next SI at once, therefore, the polling mechanism of IACG and EBU cannot be used for CBA. Because, the bandwidth allocation during C0 to C9 will be sent to ONU at the end of C9 and ONU will use these allocation results during the next SI, therefore, the computed value for R0 using this method will not be ONU true demand for next allocation cycle as traffic queues at the ONU will reduce further after the utilization of the received bandwidth allocations during C0 to C3 cycles.

To solve this problem a novel polling mechanism is proposed in which each ONU receives the upstream bandwidth allocations for the whole SI instead of receiving it every DS cycle. The ONU is required to subtract the remaining unused grant (*i*) when it is asked to send the traffic queue report so that the OLT is not required to subtract anything further from it for the computation of actual ONU bandwidth demand at the end of C9. To elaborate it further, an example scenario is considered. Assume OLT allocates 100 Bytes to TCONT (*i*) of ONU (*i*) for SI = 10 which means G0 = 100 Bytes and all the virtual allocations G1, G2, G3, G4, G5, G6, G7, G8 and G9 all will be also 100 Bytes as ONU will use the received allocation for next 10 cycles. If the length of queue of a TCONT (*i*) is assumed to be 1400 Bytes when G0 is received at the ONU then by using the polling method of EBU / IACG schemes, the ONU will compute R0 as 1400 Bytes from which G0 to G4 grants will be subtracted by the OLT to compute actual R0 = 1000 Bytes. However, the actual value of R0 should have been 400 Bytes as the ONU has already received 1000 bytes allocation that will be utilized in the current SI. Therefore, our scheme resolves this problem and makes sure that the bandwidth to be

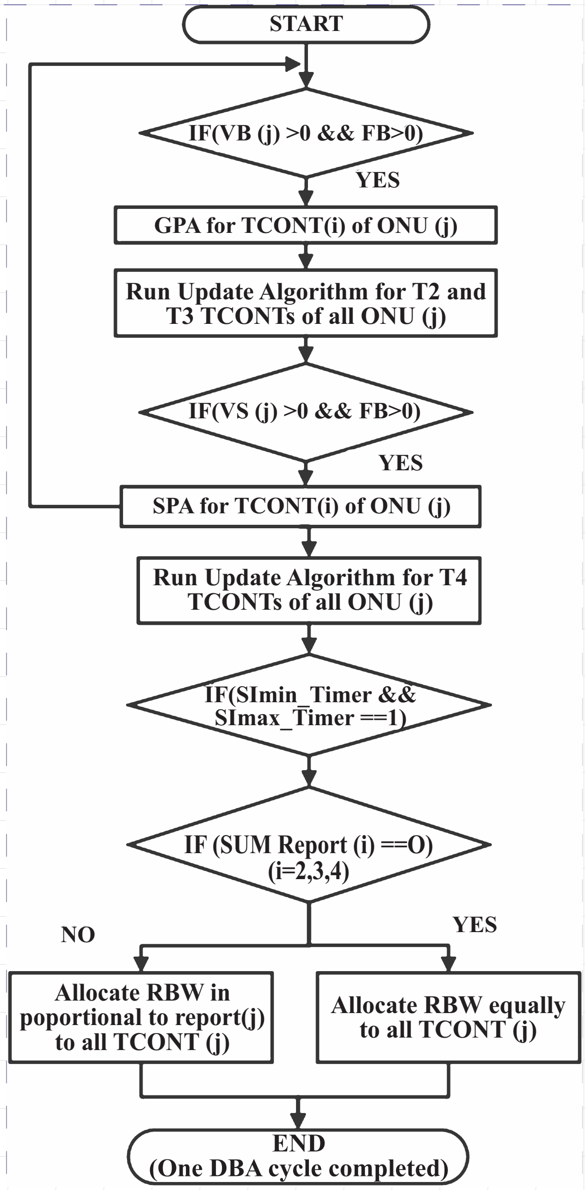

Fig. 2. Flow chart showing CBA DBA Algorithm

utilized in future US cycles at the ONU is already subtracted from the queue report being sent so that the OLT does not requires any further processing at its end. Like EBU, the CBA can allocate additional DBRu slot to ONU TCONTs if grant (*i*) > 0 during an allocation cycle.

B. *Scheduling Mechanism*

CBA follows the service parameters of ([xiii–xv]) except the polling parameters for T4. Fig. 2 illustrates the working of CBA algorithm. In each DBA cycle, first, GPA is executed and then SPA is executed. Scheduling priority is highest for the T1 TCONTs with a fixed bandwidth, followed by the assured bandwidth assignment to T2 TCONT. After this, an assured bandwidth is assigned to T3 TCONTs and then a surplus bandwidth is assigned to T3 TCONTs. Finally, the surplus bandwidth is assigned to T4 TCONTs. CBA also has two additional DBA phases; unused bandwidth assignment (UBW) and the remainder bandwidth assignment (RBW) phase. Fig. 2 shows phases involved in the scheduling process of the CBA scheme.

During the UBW, the unused bandwidth of the queues with low traffic loads is also assigned to the other queues of the same traffic class using the UBW algorithm presented in Fig. 4 of our earlier work [xxviii]. This algorithm is used for both T2 and T3 traffic classes. In addition to UBW, any remainder bandwidth is assigned to all the traffic classes of each ONU using the RBW assignment algorithm shown in Fig. 3. In IACG and EBU the UBW is divided equally to all ONU (*j*) and then in order of priority between all TCONT (*I*). This approach is not efficient and results in wastage of bandwidth if a TCONT (*i*) has no upstream traffic to send to OLT. Therefore, CBA assigns the UBW in proportion to the TCONT's demand reflected by the length of its queue report during the SI. However, due to long pause or idle time at an instant, this technique may result in zero allocation due to the sum of report (*i*) for T2, T3 or T4 (Sum_{R2}, Sum_{R3} or Sum_{R4}) becoming zero. So, in this situation, CBA assigns the UBW equally to all TCONTs to avoid bandwidth waste due to RBW not being allocated. This idle traffic condition is detected when either of the Sum_{R2}, Sum_{R3} or Sum_{R4} is be zero.

V. SIMULATION SETUP

```
{FB:Frame Bytes = 38880}
If(FB > 0)
    Share = FB
        If (Sum_R2 Or Sum_R3 Or Sum_R4 = = 0)
            FOR ( i = 0 To 15)
                ExtraBytes [i] = share / 16
                FB-=ExtraBytes [i];
                BW[index_2[k]].Grant+= ExtraBytes[i] / 3
                BW[index_3[k]].Grant+= ExtraBytes[i] / 3
                BW[index_4[k]].Grant+= ExtraBytes[i] / 3
            End For
        Else
            Share_T2 = Sum_R2 / SumAll X FB
            Share_T3 = Sum_R3 / SumAll X FB
            Share_T4 = Sum_R4 / SumAll X FB
            FB - = Share_T2 + Share_T3 + Share_T4
        End If
End If
FOR ( i = 0 To 15)
BW[index_2[k]].Grant+= Report2 [i] / Sum_R2 *Share_T2
BW[index_3[k]].Grant+= Report3 [i] / Sum_R3 *Share_T3
    BW[index_4[k]].Grant+= Report4 [i] / Sum_R4 *Share_T4
```

Fig. 3. Pseudo code for SPA for T4 and colorless grant allocation

This work uses OMNET++ with total of 16 ONU nodes and a single OLT A single splitter is used to connect these nodes with the OLT with the ONU-OLT line rate = 200 Mbps. Since, XGPON is used, the upstream and the downstream line rates are set to 2.48832 / 10Gbps. The round trip time (RTT) = 200 µs and the ONU processing time (P0) is set to 35 µs as in [xvi]. The traffic queue buffers are limited to 1 MB for each T1 to T4 traffic class. A self-similar traffic generation process is used for injecting traffic into the network to emulate an Ethernet link. The traffic generation process of [xxiii] is followed with a total of 500 truncated Pareto on-off sources. The shape parameters for the ON / OFF intervals of individual Pareto sources are set to 1.4 / 1.2 respectively. The sources are multiplexed according to their packet arrival times. The mean value of the traffic burst is set to 8000 packets. For the selection of packet lengths of the traffic frames a random process with a triangular probability distribution model with 60%, 20% and 20% probability of 64 bytes, 500 bytes and 1500 bytes frame sizes respectively is used[15], [28]. The location parameters b_{on} and b_{off} are computed from Eq. (3) and Eq. (4). The individual Pareto traffic source is generated from Eq. (5). Where *U* is a random variable and its value is chosen between 0 and 1 with a lower

TABLE II
NOMENCLATURE AND SIMULATION PARAMETERS

Symbol	Quantity
SImax_Time	Timer used to keep count of SI for GPA
SImax_Time	Timer used to keep count of SI for SPA
Abmin *ABsur*	Maximum Allocation bytes for Guaranteed / Surplus phases that can be assigned to a TCONT (*I*).
X_{pareto}	The output of a single Pareto source in Bytes.
E[on] *E[off]*	Mean on/off period in bytes of a Pareto source.
$l_{offered}$	Actual Upstream Network loads offered by all ONUs.
$index_i[k]$	An array that stores the position of grant (k) for TCONT (*i*) in BW [] array. Where k is

	chosen in a round robin manner against each *i*.
$BW[index_i[k]]$	A structure array that stores bandwidth allocations assigned to a TCONT (*i*) during a DBA cycle.
Sum_{VB2} Sum_{VB3} Sum_{VB4}	The sum of the Buffer Occupancy Reports of all ONUs for respective T2, T3 or T4 traffic TCONTs.

bound of U^{min} as $2^{(-32)}$ while b and a are either of b_{on} or b_{off}.

Traffic generator in each ONU generates same traffic load and the generated traffic frames are uniformly distributed among T1 to T4 traffic TCONTs. Overall, the average traffic for each ONU remains balanced and each ONU has an identical load.

We also consider T1 traffic and set its ABmin = 6250 with SImax = 10, which results in 40 Mbps bandwidth reservation for it. For T2 traffic, ABmin is set 12500 bytes with SImax = 10 which leads to 80 Mbps bandwidth assignment. For T3 traffic, we set ABmin = ABsur = 6250 with SImax = SImin = 10, which means an assignment of 40 Mbps for both the assured and the non-assured portions of T3. For T4 traffic, the ABsur is set to 15,624 with SImax value of 10, resulting in 100 Mbps bandwidth assignment to T4 on best effort basis. Each simulation runs until total bytes transmitted to each algorithm exceeded 10^9 in each run and offered load is varied from 0.1 to 0.99.

$$b_{on} = \left(\frac{a_{on} b_{on}{}^{a_{on}}}{a_{on}-1}\right)\left(\frac{1-(U^{min})^{\frac{a_{on}-1}{a_{on}}}}{1-U^{min}}\right) \quad (3)$$

$$b_{off} = (0.57)\,(b_{on})\left(\frac{1}{l_{Offered}} - 1\right) \quad (4)$$

$$X_{Pareto} = \frac{b}{(U)^{\frac{1}{a}}} \quad (5)$$

$$l_{offered} = \frac{E[on]}{E[on]+E\,[off]} \quad (6)$$

VI. Results and Discussion

The CBA algorithm due to its efficient utilization of UBW and RBW outperformed all other algorithms in terms of mean upstream delays, frame loss rate, unallocated bandwidth ratio and throughput for T2, T3 and T4 traffic classes as shown in Fig. 4 to Fig. 11.

As expected, the T1 traffic shows same performance with all algorithms as shown in Fig46 as it has a fixed bandwidth assignment and change of DBA does not affect it. It means upstream delay increases with an increase in load but with large variations due to bursty nature of self-similar traffic. The mean upstream delay trend of T2 and T3 TCONTs, as shown in Fig.5 and Fig.6, for all algorithms, is observed to be almost same with T3 mean delays values being slightly higher. This is because unlike T2, T3 has half bandwidth assured and half non-assured so its delay in comparison to T2 traffic only increase if it does not get a full portion of its surplus bandwidth due to all TCONTs requiring more than ABsur. In self-similar traffic, due to the occurrence of long bursts and long pause times, it is least probable that all of the ONUs have long bursts arriving for TCONT3 at the same time. Therefore, an ONU TCONT of T3 traffic mostly gets a full portion of its assured bandwidth and most of its surplus bandwidth as per its demand and thus closely matches in performance to T2 traffic. At load, higher than 0.7 CBA has only 2% to 5 % lower delays for T2 and T3 compared to EBU due to no RBW available and only update algorithm working. Overall CBA performs 2% to 62% better than EBU for both T2 and T3 and 80% to 96% better than IACG for T2 and 84% to 96.5% for T3 traffic.

For T4 traffic, as shown in Fig. 7, CBA performs much better than IACG and EBU when the traffic load is low but as the load crosses the value of 0.7, the EBU scheme closely matches the CBA performance and sometimes performs a little better due to non-availability of the FB to CBA of T4 after UBW assignment to T2 and T3 traffic.

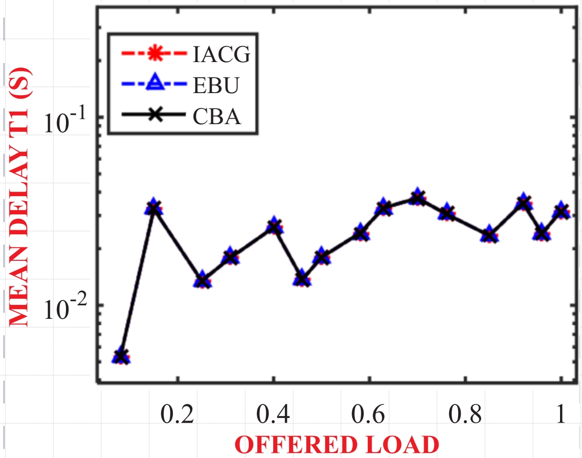

Fig. 4. Mean upstream delay of T1 Traffic

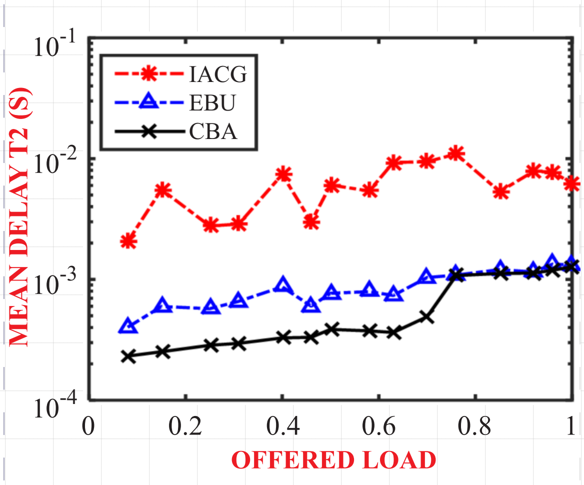

Fig. 5. Mean upstreamdelay of T2 TCONTs

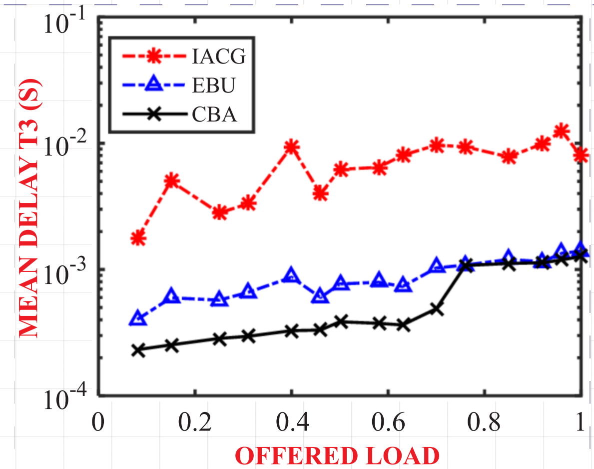

Fig. 6. Mean upstream delay of T3 TCONTs

For the overall mean upstream delay shown in Figure. 8, only T2, T3 and T4 traffic are considered as delay of T1 traffic for all algorithms is same. Due to higher mean delay values for T4 compared to T2 and T3 traffic, overall mean upstream delay follows almost the same trend as of T4.

Since IACG, EBU and CBA all utilize UBW at the end of SI, therefore, the unallocated bandwidth ratio for all should be ideally zero but practically all the unassigned bandwidth cannot be equally divided and there is some remainder bandwidth. This remainder is minimum in case of CBA due to better utilization of RBW and UBW as shown in Fig. 9.

Frame loss occurs at ONU when its buffer is full and newly arrived traffic frames cannot be stored. This

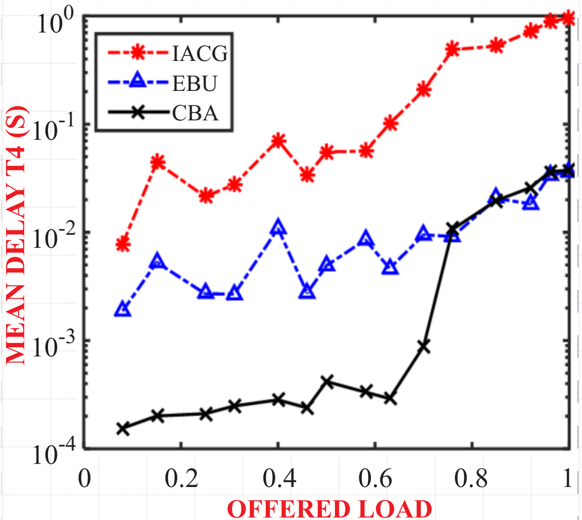

Fig. 7. Mean upstream delay of T4 TCONTs

is more likely at higher loads but due to busty nature of self-similar traffic, frame loss may also sometimes occurs even at when the traffic load due to the sudden arrival of a unusually longer traffic stream [xl]. Due to higher queuing delays IACG shows highest frame losses for its all traffic classes. CBA shows lowest frame losses.

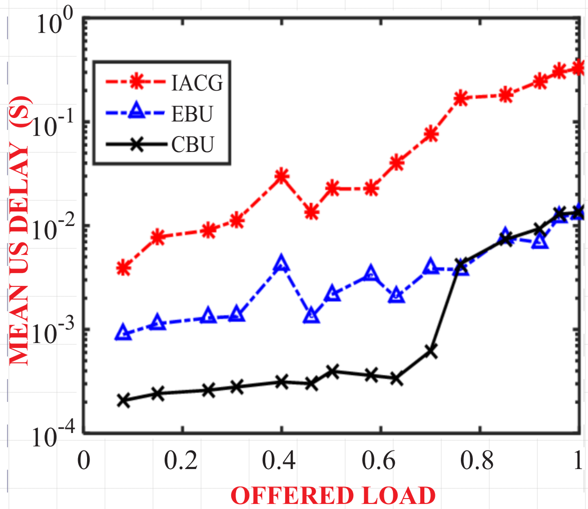

Fig. 8. Overall Mean upstream delay

Fig. 11 compares the performance of all algorithms in terms of throughput. Due to higher frame loss IACG shows the lowest throughput especially at higher loads. CBA shows up to 7% and 12% higher throughput compared to EBU and IACG algorithms.

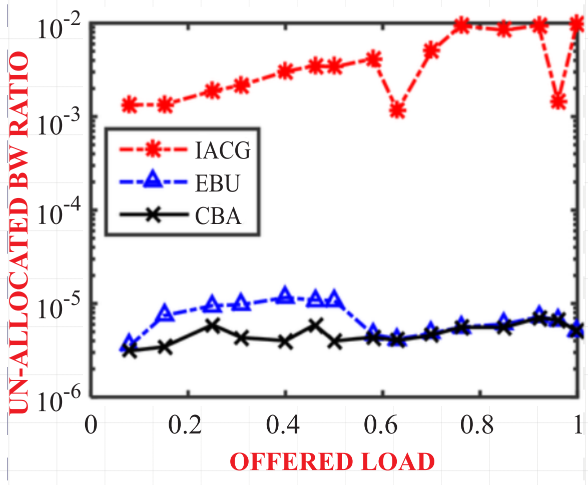

Fig. 9. Unallocated Bandwidth Ratio

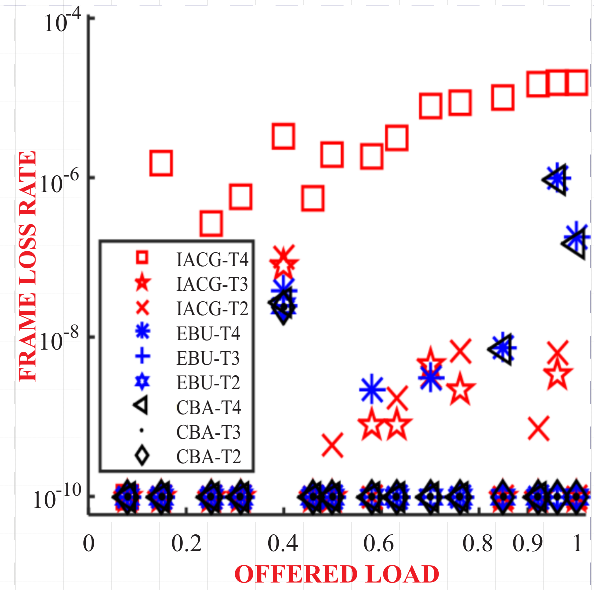

Fig. 10. Frame Loss Rate

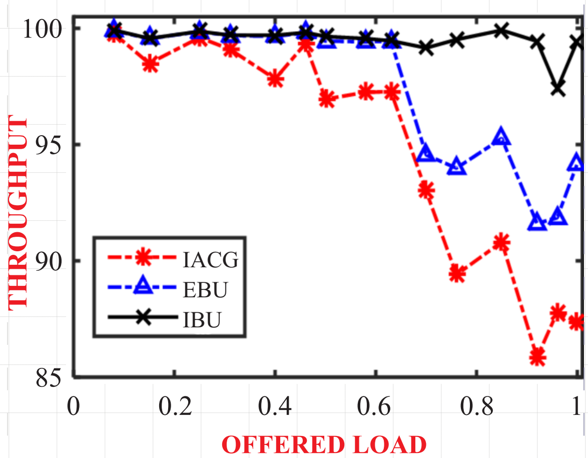

Fig. 11. Algorithm Throughput

VII. CONCLUSION

This study provides a comprehensive review of the dynamic bandwidth mechanism for PON. It classifies the different DBA schemes on the basis of their polling and scheduling mechanisms. A new DBA mechanism for XGPON with a novel polling mechanism is also proposed to solve the IBR problem and improve the mean upstream delays and frame loss rate of all traffic classes as well as overall throughput by efficiently utilizing the available bandwidth in RBW and UBW phases during the DBA process. The Update algorithm in CBA assigns all unused bandwidth to ONU TCONTs with negative VB (i) in a fair manner. The RBW assignment algorithm makes the allocation in proportion to the demand of a TCONT (*i*) to avoid bandwidth waste. The proposed novel polling mechanism collects accurate buffer occupancy reports from ONUs without requiring any further operation at OLT to compute actual ONU demand. CBA shows better performance versus both EBU and IACG in our PON simulation test bed.

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