# A Scalable Interleaved DBA Mechanism within Polling Cycle for the Ethernet Passive Optical Networks

**I-Shyan Hwang , Jhong-Yue Lee , Zen-Der Shyu**

*Abstract*—**Ethernet Passive Optical Networks (EPONs) are designed to deliver multiple services and applications, such as voice communications, standard (SDTV) and high-definition video (HDTV). To support these applications and their various requirements, EPONs require Quality-of-Service (QoS) mechanisms to be built in service. For this purpose, a scalable Interleaved Dynamic Bandwidth Allocation (IDBA) mechanism for sharing the uplink bandwidth among optical network units (ONUs) is proposed in this paper. The modus operandi of IDBA is to divide the cycle time by partitioning the ONUs into two groups with some timing overlap to execute interleaved bandwidth allocation, which cooperates with Limited Bandwidth Allocation (LBA), Excess Bandwidth Reallocation (EBR) and accurate prediction mechanism in EPONs. The proposed IDBA mechanism has two advantages, namely it eliminates the idle period problem in the traditional DBA mechanism, and guarantees QoS services by dynamically adjusting the bandwidth within the group of subscribers. This will not only support the differentiated services architecture but also offer various QoS levels. Simulation results obtained show that the proposed IDBA mechanism achieves desirable system performance relative to packet delay, jitter performance, throughput, ratio of packet loss and fairness.**

*Index Terms*—**EPON, QoS, IDBA, system performance, EBR.**

## I. Introduction

Due to the rapid and consistent increase in network traffic generated by domestic and small business users over the last few years, broadband access networks have become increasingly important. However, though various technologies have been used to provide broadband access to networks in the area known as the "last mile" [1], they cannot simultaneously upgrade the current access network whilst providing a low-cost and high-speed solution for broadband access services. One possible solution is Ethernet Passive Optical Network (EPON) that has been discussed in IEEE 802.3ah as one of the extensions of Gigabit-Ethernet [2]. It has been regarded as a promising solution for next generation fiber-based access due to its simplicity, cost-effectiveness and scalability. The EPON architecture, as shown in Fig. 1, consists of a centralized optical line terminal (OLT) and a number of splitters. It connects a group of associated optical network units (ONUs) over point-to-multipoint topologies to deliver broadband packets and reduces costs relative to maintenance power. EPON also provides bi-directional transmissions, i.e. downstream transmission from OLT to ONUs and upstream transmission from ONUs to OLT in sequence. In the downstream transmission, all control messages and the data packets are carried and broadcasted from the OLT passing through a 1:N passive splitter or a cascade of splitters to each ONU through the entire bandwidth of one wavelength as a downstream channel. In the upstream transmission, all ONUs share the common transmission channel towards the OLT, and only a single ONU may transmit data in its time slot to avoid data collisions. It can be noted that a robust mechanism is necessary for allocating time slots and upstream bandwidth for each ONU to transmit the data. To avoid data collision, the multi-point control protocol (MPCP) is introduced on EPON, and two media access control (MAC) messages: GATE and REPORT messages are included in MPCP protocol [3].

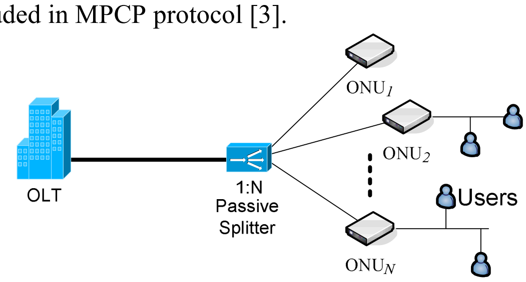


Figure 1. Tree-based PON topology

In the traditional DBA scheme, the OLT will begin bandwidth allocation after collecting whole REPORT messages, resulting in the *idle period problem* (as shown in Fig. 2). To elaborate, the idle period is the sum of the computation time of DBA and the round trip time between OLT and each ONU (N.B. ONUs cannot transmit data during the idle period). Hence, for the DBA scheme, reducing the idle period becomes one of the important issues to address in order to improve bandwidth utilization. Another problem with the DBA scheme is that the queue state is inconsistent due to packets that continue to arrive during this waiting time. To

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clarify this problem, refer Figure 3 illustrates the *waiting time*, $t_2 - t_1$, which is the time elapsed from when the packets begin to arrive to before the start of data transmission. In the DBA scheme, each ONU experiences a waiting time between sending the REPORT message and sending the buffered frames. Consequently, packets that arrive during the waiting time have to be delayed to the next transmission cycle, potentially leading to longer delays. To address this, predictive schemes can be used so that traffic arrival during the waiting time is taken into consideration to avoid longer packet delay and network performance degradation.

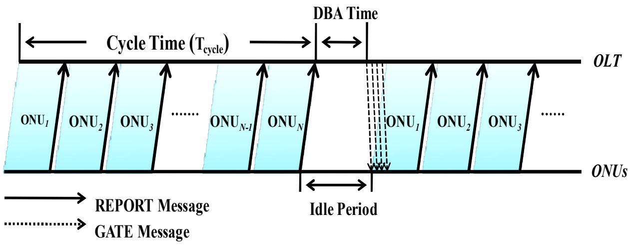


Figure 2. Traditional DBA mechanism

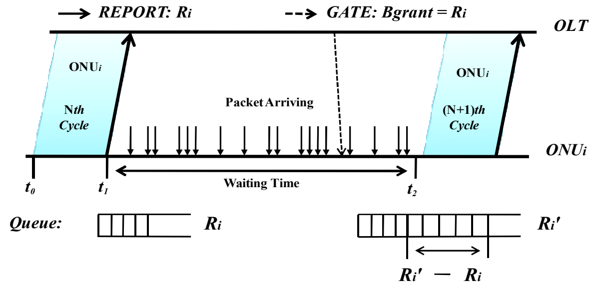


Figure 3. Queue state between waiting time

In this paper, the problem of inconsistent queue states caused by waiting time is considered and an accurate prediction mechanism is proposed to reduce packet delay and allocate bandwidth efficiently. We also discuss the precision of an accurate traffic prediction mechanism, which is necessary to avoid over-estimation or under-estimation that can result in longer packet delays and degrade the network performance [8-11]. Although exhaustive queue size prediction mechanism have been proposed (which can be credit-based [7,8,12], linear-based [5,8,9], proportion-based [9,13], waited-based [4] or QoS-based [6,7,10,11,14]), these traffic prediction mechanism are unable to provide feasible solutions for differentiated services and have not addressed the queue size inconsistent problem. In this paper, the proposed traffic prediction mechanism supports differentiated services with their various requirements.

Previous researches have suggested that the maximum of $T_{cycle}$ is 1*ms* [15,16], which is set to meet the ITU-T recommendation, G.114, i.e. the delay for voice traffic in the access network to be set at 1.5*ms* [17]. On one hand, making $T_{cycle}$ too large will lead to longer packet delays for all Ethernet frames because a larger cycle time incurs a larger transmission window size and results in the ONU ineffectively holding the transmission channel. As a result, the backlogged traffic at the next ONU experiences longer packet delays. On the other hand, making $T_{cycle}$ too small will result in more bandwidth being wasted by guard intervals and an increase in CPU processing load.

From our previous studies [9], we noted that the idle period problem of IPACT can be resolved by using Early-DBA mechanism with Prediction-based Fair Excessive Bandwidth Reallocation Scheme (PFEBR), which includes the unstable degree list to provide more accurate predictions. However, the Early-DBA has a jitter performance problem, which is due to a change in the transmission orders of some ONUs. A scalable Interleaved Dynamic Bandwidth Allocation (IDBA) mechanism is proposed in this paper, which uses the concept of Early-DBA to resolve the idle period problem. Nevertheless, the proposed IDBA does not change the granting order for ONUs to reduce the jitter problem.

In proposed IDBA mechanism, shown in Fig. 4, the $T_{cycle}$ is divided by halving the ONUs. One part is the first subgroup (*Group1*) of ONUs, which is denoted by $S_{n,1}$ transmission time for cycle *n*, and the other part is the second subgroup (*Group2*) of ONUs, which is denoted by $S_{n,2}$ transmission time for cycle *n*. The subgroup $S_{n+1,1}$ upstream transmission period is calculated in the nth cycle. At *Group2* DBA time, the OLT performs the DBA computation for ONUs in subgroup $S_{n,2}$. At this time, the OLT has granted the GATE message to ONUs in subgroup $S_{n+1,1}$, so that the ONUs in subgroup $S_{n+1,1}$ can transmit upstream data during idle time while the OLT computes DBA for subgroup $S_{n+1,2}$ (*Group2* DBA). ONUs in subgroup $S_{n+1,2}$ is allowed to transmit upstream data as soon as the last ONU in subgroup $S_{n+1,1}$ finishes transmission. Then, ONUs in *Group1* DBA time also performs what *Group2* DBA time has done in the same way. The OLT lets the DBA process execute the QoS-based prediction, the limit bandwidth allocation (LBA), and the excessive bandwidth reallocation (EBR) for each part. When the predicted bandwidth has been over-estimated, the unused bandwidth is simply reserved for the next part, and the total transmission time of two successive parts is limited in one $T_{cycle}$. The proposed IDBA has two contributions: one is eliminating the idle period problem in the traditional DBA mechanism, and the other is ensuring QoS services by dynamically adjusting the bandwidth between $S_{n,1}$ and $S_{n,2}$, which not only supports differentiated services architecture but also offers various levels of QoS.

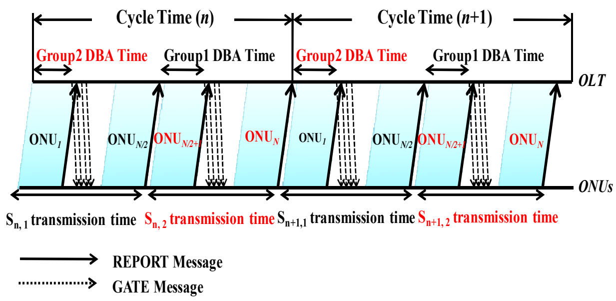


Figure 4. Operation of the proposed IDBA mechanism

The rest of this paper is organized as follows. Section II presents the proposed interleaved DBA and QoS-based scheduling scheme. Simulation evaluations are presented in Section III, and conclusions are drawn in Section VI.

## II. Proposed Interleaved DBA Mechanism

The Interleaved Dynamic Bandwidth Allocation (IDBA) mechanism is proposed to resolve the *idle period problem* and enhance the QoS for differentiated services by using prediction and EBR in the EPON system. The flowchart of the IDBA mechanism is illustrated in Fig. 5, where $P_{n,j}$ is defined

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as the bandwidth request prediction of ONU$_j$ for cycle $n$, $S_{n,i}B_j^{Min}$ is defined as the minimum guaranteed bandwidth belonging to part $i$ of ONU$_j$ for cycle $n$, which can be calculated by the service level agreement (SLA), $B_{excess}$ the excess bandwidth which is calculated by the sum of the under exploited bandwidth of lightly-loaded ONUs and $B_{remain}$, the unused bandwidth after excess bandwidth reallocation from heavily-loaded ONUs.

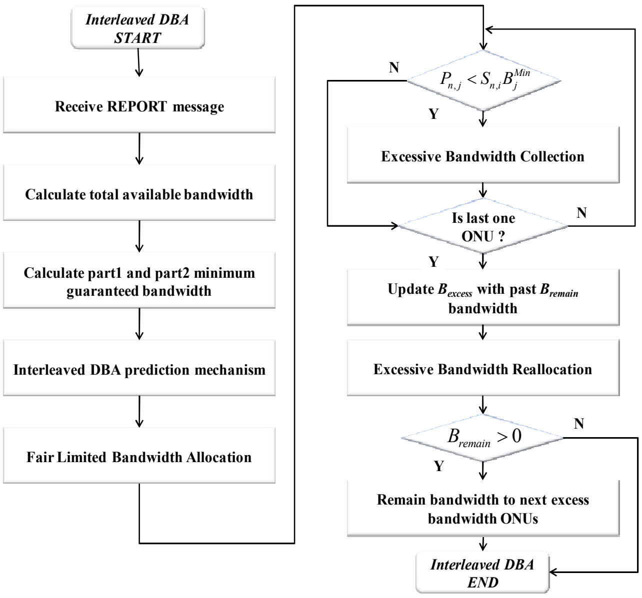



Figure 5. Flowchart of IDBA mechanism

When receiving whole REPORT messages from each ONU, the total available bandwidth can be calculated as $(r\times(T_{cycle}^{Max}-N\times T_g)-N\times 512)$, where $r$ is the transmission speed of the EPON in bits per second, $T_{cycle}^{Max}$ is the maximum cycle time, $N$ is the number of ONUs, $T_g$ is the guard time and the control message length is 512bits for the EPON system. Next, the QoS-based IDBA executes the prediction mechanism based on the current traffic status. The limited bandwidth allocation mechanism then compares the minimum guaranteed bandwidth with the predicted bandwidth of each ONU. If $P_{n,j} \le S_{n,i}B_j^{Min}$, then excessive bandwidth collection for lightly-loaded ONUs is executed, followed by excessive bandwidth reallocation mechanism for heavily-loaded ONUs. In the end, the unused bandwidth from the over-estimated bandwidth can be reserved for the next group of ONUs for DBA. Therefore, the IDBA can support QoS and enhance system performance for differential services and efficiently reallocates excessive bandwidth in EPON. The prediction mechanism of IDBA is described in Section A, limited bandwidth allocation (LBA) mechanism with fairness in Section B and excessive bandwidth reallocation (EBR) mechanism in Section C respectively.

Initially, the available bandwidth for part one, $S_{n,1}B_{available}$, and part two, $S_{n,2}B_{available}$, for cycle $n$, can be calculated by applying equations (1) and (2).

$$S_{n,1}B_{available} = total\ availible\ bandwidth\ \times\left(1-\sum_{j=N/2+1}^{N} S_{n,2}W_j\right) \quad (1)$$

$$S_{n,2}B_{available} = total\ availible\ bandwidth\ \times\left(1-\sum_{j=1}^{N/2} S_{n,1}W_j\right), \quad (2)$$

where $W_j$ is the weight assigned to each ONU$_j$ based on its SLA.

### *A. Interleaved DBA prediction mechanism*

In relation to resolving queue variation between waiting times and reducing the packet delay, the prediction mechanism of IDBA takes differential traffic characteristic into account to enhance the prediction accuracy for each ONU. In this paper, we divide traffic data into three priority classes, EF, AF, and BE by the definition of Differentiated Services [8,18]. To achieve better performance for a time-critical application, for instance constant bit rate (CBR) for EF traffic and non-busty traffic mode, bandwidth should be assigned to the ONUs according to the rate of these applications. Therefore, the proposed prediction mechanism assigns the CBR bandwidth to EF traffic as it multiplies the previous request of EF by one plus the proportion of waiting time, $T_{waiting,j}$, and cycle time, $T_{cycle,j}$, for ONU$_j$. Moreover, the traffic characteristic of AF and BE are variable bite rate (VBR) and busty traffic mode, and the proposed prediction mechanism**s** of AF and BE traffic compare the difference between the requested transmission window at the present cycle and a mean value requested transmission window of historical cycles. The predicted value of bandwidth requirements for differentiated traffic is expressed in equation (3), where $R_{n,j}^T$ represents bandwidth request of each traffic type of ONU$_j$ in cycle $n$, and $\overline{H_j^T}$ is the average bandwidth requirements of the history cycle of each traffic type of ONU$_j$, where $T\in\{EF,AF,BE\}$.

$$\begin{cases} P_{n,j}^{EF} = \overline{H_j^{EF}} \times (1+T_{waiting,j}/T_{cycle,j}) \\ P_{n,j}^{AF} = R_{n,j}^{AF} - \overline{H_j^{AF}} \\ P_{n,j}^{BE} = R_{n,j}^{BE} - \overline{H_j^{BE}} \end{cases} \quad (3)$$

After the traffic forecast value is calculated in each ONU, the prediction mechanism can derive $P_{n,j}^T$ which represents the prediction value of each ONU$_j$ in cycle $n$, where $T\in\{EF,AF,BE\}$. For AF and BE traffics, if $P_{n,j}^T > 0$, the demand tends to increase gradually and so we update the forecast value to obtain the new bandwidth requirements. Otherwise, if $P_{n,j}^T \le 0$, we do not update.

### *B. Fair limited bandwidth allocation mechanism*

During dynamic allocation, the allocated timeslot will be adapted to the requested bandwidth. To prevent the allocation of excessive bandwidth (which can increase packet delay) or too little bandwidth (which can result in wasted bandwidth), the proposed LBA is set as $S_{n,i}G_j = \min(P_{n,j}, S_{n,i}B_j^{Min})$, where $S_{n,i}G_j$ is the granted bandwidth timeslot in GATE message for ONU$_j$ (which belongs to the $i$th part in the $n$th cycle), $P_{n,j}$ is the predicted value of bandwidth requirements for ONU$_j$, and $S_{n,i}B_j^{Min}$ is the minimum guaranteed bandwidth of ONU$_j$ (which belongs to the $i$th part in the $n$th cycle) that will equalize the bandwidth for each ONUs in part $i$. If $P_{n,j} < S_{n,i}B_j^{Min}$, the limited granted bandwidth from the OLT is the same as the predicted bandwidth; otherwise, the grant for the ONU$_j$ equals $S_{n,i}B_j^{Min}$. The proposed LBA not only solves the problem of an ONU with heavy traffic load monopolizing the upstream channel, but also supports the priority servicing of differentiated services to guarantee QoS. The $S_{n,i}B_j^{Min}$ and $S_{n,i}G_j^T$, where $T\in\{EF,AF,BE\}$, in GATE message based on each traffic class are described as follows:

$$S_{n,i}B_j^{Min} = \frac{S_{n,i}B_{available}}{Numbers\ of\ S_{n,i}\ ONU} \quad (4)$$

$$\begin{cases} S_{n,i}G_j^{EF} = \min(P_j^{EF}, S_{n,i}B_j^{Min}) \\ S_{n,i}G_j^{AF} = \min(P_j^{AF}, S_{n,i}B_j^{Min} - S_{n,i}G_{j,n+1}^{EF}) \\ S_{n,i}G_j^{BE} = S_{n,i}B_j^{Min} - S_{n,i}G_j^{EF} - S_{n,i}G_j^{AF} \end{cases} \quad (5)$$

### C. Excessive bandwidth reallocation mechanism

After LBA grants all bandwidth timeslot to the active ONU$_j$, lightly loaded ONUs with bandwidth requirements less than the $S_{n,i}B_j^{Min}$ may still be present. The sum of the under utilized bandwidth of lightly-loaded ONUs, excessive bandwidth ($B_{excess}$)[9,10], can be expressed as equation (6).

$$B_{excess} = \sum_{j \in L} (S_{n,i}B_j^{Min} - P_{n,j}) \quad (6)$$

where $S_{n,i}B_j^{Min} > P_{n,j}$, L is the set of lightly-loaded ONUs and *j* is a lightly-loaded ONU in L.

In the proposed EBR mechanism, $B_{excess}$ is redistributed among the heavily-loaded ONUs. A heavily-loaded ONU obtains an additional bandwidth based on the EBR mechanism. If the bandwidth has not yet been distributed to the heavily-loaded ONUs after $B_{excess}$ has been allocated, we assign the remaining available bandwidth as $B_{remain}$, which can be retained to the next excessive bandwidth collection to enhance the bandwidth efficiency in the next cycle. It also needs to be noted that $B_{remain}$ must be restricted at half cycle time to avoid the piling up of unused available bandwidth , which can result in unfair resource distribution. The EBR mechanism gives considerable improvement in average packets delay and network throughput as indicated by the reported simulation results. $B_{remain}$ is expressed in equation (7) as follows:

$$B_{remain} = B_{excess} - \sum_{j \in H} (P_{n,j} - S_{n,i}B_j^{Min}) \quad (7)$$

where $S_{n,i}B_j^{Min} < P_{n,j}$, H is the set of heavily-loaded ONUs and *j* is a heavily-loaded ONU in H. The proposed EBR mechanism operational procedure is illustrated in Fig. 6. After EBR, if the excessive bandwidth is larger than the sum of the bandwidth request among the heavily-loaded ONUs, then the excess bandwidth can satisfy the extra requirement of the heavily-loaded ONUs completely. $B_{remain}$ can then be calculated by using equation (7), which can be retained as excessive bandwidth for the next ONUs group.

The proposed EBR mechanism in the IDBA can provide fairness to EBR based on the guaranteed bandwidth rather than the requested bandwidth, with no partiality and increase in bandwidth utilization. Moreover, the EBR mechanism not only alleviates the unfairness problem but also supports QoS by fairly distributing in a priority manner to improve LBA scheduling and enhance the traffic class.

## III. Performance Evaluation

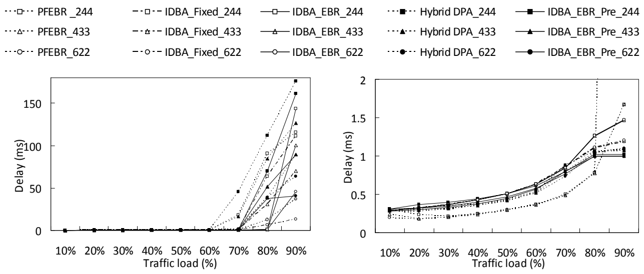
In this section, comparisons are performed using the PFEBR scheme, IDBA_Fixed without LBA, EBR and prediction, IDBA_EBR without prediction mechanism, IDBA_EBR_Pre incorporated QoS-based prediction with EBR, hybrid double-phase polling algorithm (DPA)[7], with respect to end-to-end delay, throughput, jitter performance, ratio of packet loss and fairness. The system model is set up within the OPNET simulator with one OLT and 32 ONUs. The simulation scenario is summarized in Table 1. For the traffic model considered, an extensive study has shown that most network traffic can be characterized by self-similarity and long-range dependence (LRD) [19]. In order to simulate the effect of high priority traffic, the proportion of traffic profile is analyzed by simulating the three significant scenarios in (EF, AF, and BE) with (20%, 40%, 40%), (40%, 30%, 30%), and (60%, 20%, 20%), respectively [10,20].

Table 1. Simulation scenario

| | |
|---|---|
| Number of ONUs in the system | 32 |
| Upstream/downstream link capacity | $1Gbps$ |
| OLT-ONU distance (uniform) | $10-20\,km$ |
| Buffer size | $10M$ |
| Maximum transmission cycle time | $1\,ms$ |
| Guard time | $5\,\mu s$ |
| Computation time of DBA | $10\,\mu s$ |
| Control message length | $64bytes$ |

### A. End-to-end packet delay

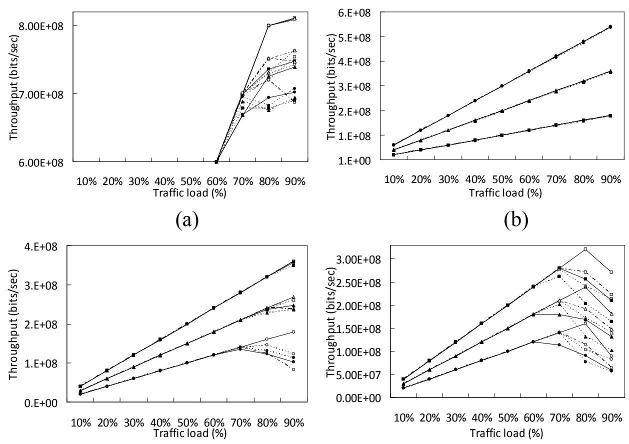
Figure 7 compares the mean end-to-end packet delay and EF traffic classes with end-to-end delay vs. different traffic loads for PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA. The simulation results obtained show that hybrid DPA has a higher average end-to-end packet delay than IDBA when the traffic load exceeds 60%. However, the mean end-to-end packet delay of IDBA_Fixed and IDBA_EBR_Pre increased when traffic load exceeded 70% while for IDBA_EBR, it increased when traffic load exceeded 80% regardless of the scenario. One possible reason is that the *idle period problem* can be resolved by IDBA mechanism and that the excess bandwidth can be reallocated effectively by using the EBR mechanism. Additionally, the EBR mechanism in IDBA mechanism that is based on the guaranteed bandwidth and exceeds requested bandwidth not only guarantees bandwidth but also avoids over-allocation. Figure 7(a) shows that the IDBA mechanism has better performance in terms of mean end-to-end packet delay when the ratio of EF traffic increases. One possible reason is that the network environment will converge to a stable state when the proportion of CBR traffic and the IDBA mechanism satisfies the bandwidth requirements of EF traffic first and then the requirements of AF and BE traffics in LBA and EBR. To enhance the performance of high priority traffic, the QoS-based prediction mechanism decreases the resources allocated to low priority traffic and allocates more resources to EF traffic which will decrease the overall system performance when the proportion of VBR traffic is higher. Figure 7(b) shows that the IDBA_EBR_Pre can guarantee the bandwidth for EF traffic class, and result in lower EF end-to-end delay for each ONU. The PFEBR mechanism can reduce the overall EF traffic delay through using the accurate prediction mechanism but with a traffic load of 90%. The IDBA mechanism meets the ITU-T recommendation G.114 that specifies the delay for voice traffic in the access network at 1.5*ms* [17]. The end-to-end delay of EF traffic in the proposed method can be guaranteed regardless of the proportion of EF traffic.




(a) (b)

Figure 7. (a) Average end-to-end packet delay and (b) EF end-to-end delay vs. different traffic loads for PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA.

## B. System throughput



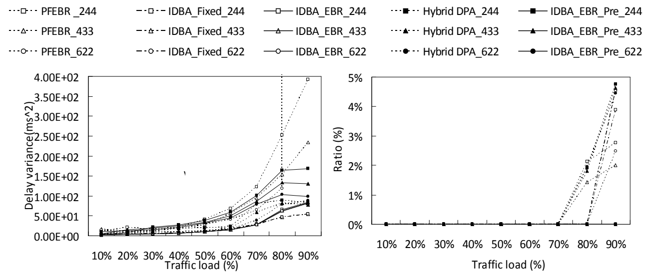

(a) (b)

(c) (d)

Figure 8. (a) Mean system throughput and (b) EF traffic throughput (c) AF traffic throughput (d) BE traffic throughput vs. different traffic loads for PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA.

Figure 8 shows the mean system throughput and EF, AF, BE traffic throughput against different traffic loads for the PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA. Figure 8(a) shows that the proposed IDBA mechanism outperforms hybrid DPA in mean system throughput, and this is because interleaved transmissions can eliminate the problem of idle time in traditional DBA and support efficient EBR as well as the interleaved remain compensation mechanism. The four mechanisms have the same mean system throughput until the traffic load exceeds 60%. The PFEBR and hybrid DPA has gradually achieved a consistent performance when the traffic load exceeds 60%. In this case, the IDBA_EBR has the best mean throughput performance and begins to become saturated when traffic load exceeds 80% due to effective excess bandwidth reallocation and the interleaved remain compensation mechanism. As for the EF throughput, as shown in Fig 8(b), the proposed IDBA_EBR_Pre mechanism outperforms the other mechanisms because the EF traffic obtains additional bandwidth by using QoS-based prediction mechanism which can enhance high priority traffic adaptively for different traffic proportions. For the AF and BE throughput, as shown in Fig 8(c) and Fig 8(d), the IDBA_EBR has the best throughput performance because the guaranteed bandwidth can enhance requirements of the subscriber, and at the same time not over-estimate the demand of bandwidth allocation for subscribers. The AF throughput performance of hybrid DPA begins to decrease when traffic load exceeds 70% in scenario (40%, 30%, 30%) and scenario (60%, 20%, 20%); whereas the BE throughput performance of hybrid DPA begins to decrease when traffic load exceeds 70% in every scenario. One possible reason is that the QoS-based prediction mechanism of hybrid DPA guarantees the requirement of high priority and disregards the requirement of low priority traffic (which results in lower AF and BE throughput) when the proportion of EF traffic is high.

## C. EF jitter and Packet loss ratio




(a) (b)

Figure 9. (a) EF jitter and (b) Average packet loss ratio vs. different traffic loads for PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA.

Figure 9 shows the comparison of delay variance of EF class and packet loss against different traffic loads among PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA, respectively. In the proposed IDBA mechanism, we can see that the EF jitter of PFEBR can be improved by using IDBA, especially IDBA_Fixed. The reason is that the transmission order of each ONU is sequential and that PFEBR changes the transmission order of ONUs. However, IDBA_EBR_Pre has a higher EF jitter when the traffic load exceeds 60%, especially in scenario (20%, 40%, 40%). This could be due to the prediction mechanism allocating additional prediction bandwidth according to the requirements of subscribers and therefore, yields a larger ratio of VBR traffic in scenario (20%, 40%, 40%). Figure 9(b) shows that the hybrid DPA begins to have packet loss when the traffic load exceeds 70% in every scenario due to over allocation of the requested bandwidth to ONUs [21] for the EBR mechanism in hybrid DPA. This is termed the *redundant bandwidth problem* [9] to decrease overall system throughput. IDBA_Fixed starts to have packet loss when traffic load exceeds 80% in every scenario because lake an effective excess bandwidth reallocation mechanism. Furthermore, IDBA integrates the EBR and remaining bandwidth compensation mechanism to improve bandwidth utilization that prevents packet loss build up in high traffic load for each scenario.

## D. Fairness

Figure 10 shows the comparison of fairness against different traffic loads among PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA, respectively. Recently, fairness and QoS on DBA schemes have become important issues, which we are also evaluating. The fairness index $f$ ($0 \leqq f \leqq 1$) has been addressed [22] which is defined as equation (8)

$$f = \frac{\left(\sum_{i=1}^{N} G_{[i]}\right)^2}{N \sum_{i=1}^{N} G_{[i]}^{\;2}} \quad (8)$$

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,where $N$ is the total number of ONUs and $G_{[i]}$ is the granted bandwidth of $ONU_i$. Jain's fairness index $f$, ranging from 0 to 1, becomes 1 when all ONUs have the same amount of bandwidth allocated by the OLT. Simulation results show that Jain's fairness index $f$ of IDBA is better than hybrid DPA, especially in IDBA_EBR_Pre when the traffic load exceeds 70%. IDBA_EBR_Pre has the best fairness performance, where the average Jain's fairness index $f$ is about 0.9. One possible reason of this is that the proposed IDBA_EBR_Pre utilizes the idle period and remaining bandwidth by performing DBA computation for fair bandwidth allocation and that the fairness EBR mechanism is based on the guaranteed bandwidth rather than requested bandwidth, with no partiality and increase in bandwidth utilization. The fairness of hybrid DPA begins to gradually vary from traffic load 40% to traffic load 70%. Two possible causes of this is that 1) the hybrid DPA changes the transmission mechanism between online polling and double phase polling and 2) the EBR based on the requested bandwidth in hybrid DPA has some drawbacks, namely unfairness and excessive bandwidth allocated to ONUs over what has been requested.

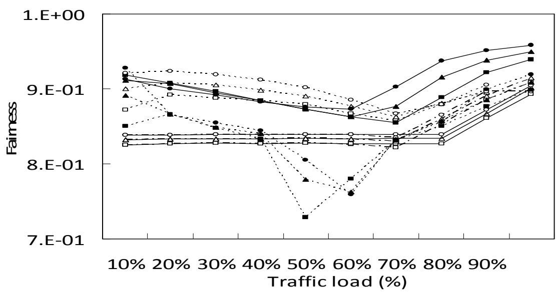


Figure 10. Fairness using Jain's index vs. different traffic loads for PFEBR, IDBA_Fixed, IDBA_EBR, IDBA_EBR_Pre and hybrid DPA.

## IV. Conclusions

In this study, important factors that can improve the performance of EPON are discussed and evaluated. The IDBA mechanism executes an interleaved transmission process to automatically adjust cycle time to resolve the *idle period problem* for traditional DBA scheme, enhancing the system performance to reduce end-to-end packet delay and improving the throughput. Moreover, it not only accounts for the prediction for differential traffic characteristic but also allocates bandwidth for differential traffic adaptively and improves the utilization of bandwidth by using EBR and the remaining bandwidth compensation mechanism. The simulation results obtained show that the throughput of IDBA is better than that of PFEBR and hybrid DPA, especially in relation to EF traffic performance and average packet loss ratio. Furthermore, the proposed QoS-based prediction mechanism outperforms the hybrid DPA by lowering the EF packet delay. Finally, the IDBA can effectively improve the EF jitter problems faced by PFEBR. It makes use of excess bandwidth and remaining bandwidth to have higher system throughput, lower packet loss and end-to-end delay of each ONU. Future work includes finding out the optimal number of subgroups and having a more appropriate prediction mechanism to improve system performance.

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