Enhanced Dynamic Bandwidth Allocation Algorithm in Ethernet Passive Optical Networks

Byungjoo Park, Ankyu Hwang, and Jae Hyoung Yoo

As broadband access is evolving from digital subscriber lines to optical access networks, Ethernet passive optical networks (EPONs) are considered a promising solution for next generation broadband access. The point-to-multipoint topology of EPONs requires a time-division multiple access MAC protocol for upstream transmission. In this paper, we propose a new enhanced dynamic bandwidth allocation algorithm with fairness called EFDBA for multiple services over EPONs. The proposed algorithm is composed of a fairness counter controller and a fairness system buffer in the optical line terminal. The EFDBA algorithm with fairness can provide increased capability and efficient resource allocation in an EPON system. In the proposed EFDBA algorithm, the optical line termination allocates bandwidth to the optical network units in proportion to the fairness weighting counter number associated with their class and queue length. The proposed algorithm provides efficient resource utilization by reducing the unused remaining bandwidth made by idle state optical network units.

Keywords: Ethernet passive optical network, bandwidth allocation, fairness.

I. Introduction

Recently, broadband access technologies such as xDSL have been rapidly deployed. However, signal attenuation in long copper line and crosstalk interference thwart xDSL from simultaneously achieving high bit-rate and long reach.

Currently, local exchange carriers are migrating to passive optical networks (PONs) for next-generation last mile solutions [1], [2]. The Ethernet passive optical network (EPON) is considered a neat solution for implementing fiber-to-the-home. It has a point-to-multipoint tree topology, which carries 802.3 Ethernet frames between an optical line termination (OLT) and multiple optical network units (ONUs) via a passive optical splitter [3]. To share the upstream bandwidth among ONUs while avoiding collisions, robust and efficient medium access control is required [4]-[6].

Figure 1 shows the traffic flow for the downstream and upstream between OLT and *N* ONUs. For downstream transmission, an OLT broadcasts a frame to all ONUs, and

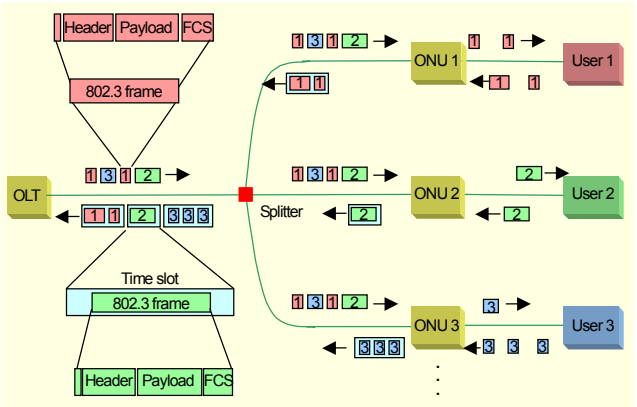


Fig. 1. Upstream and downstream traffic flow in EPON.

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each ONU filters the received frame according to its logical link ID. For upstream transmission, ONUs must share a single fiber from a splitter to an OLT, and a medium access control protocol is essential to avoid a time collision. To resolve the upstream bandwidth allocation problem, a handshaking procedure between an ONU and an OLT is defined in the multipoint control protocol (MPCP) of IEEE 802.3ah Ethernet in the First Mile standard [7]. The MPCP is mainly based on two control messages: the report message, which contains the number of time slots an ONU needs, is sent by an ONU to an OLT; the gate message, which contains a grant indicating the start time of frame transmission and the duration, is sent by an OLT to an ONU. Bandwidth allocation operates in a master and slave architecture. An OLT is the master, and ONUs are slaves. In addition, an OLT allocates each ONU an appropriate upstream bandwidth based on the ONU's requests. The MPCP defines only the exchange procedure of the control message and does not specify how to calculate and allocate bandwidth dynamically upon an ONU's request. Consequently, the dynamic bandwidth allocation (DBA) scheme, which greatly affects EPON performance, is an open issue. A few trials have been developed to increase bandwidth utilization employing a more efficient DBA scheme, such as interleaved polling with adaptive cycle time for DBA [5], [8], [9]; dynamic bandwidth allocation schemes to improve utilization under non-uniform traffic in EPON [10], [11]; and a sliding cycle time-based MAC protocol for service level agreeable Ethernet passive optical networks (SLICT) [12]. In interleaved polling with adaptive cycle time (IPACT) [5], the limited service scheme grants the requested window timeslot size, which cannot exceed $W_{\max}$. Equation (1) shows the granted window timeslot size at (k+1)th cycle for ONU$_i$ in the limited scheme.

$$W_i^{k+1} = \begin{cases} R_i^k & \text{if} \quad R_i \le W_{\max}, \\ \min(R_i^k, W_{\max}) & \text{otherwise}, \end{cases} \tag{1}$$

where $W_{\max}$ is the maximum window timeslot size for ONUs; R_i is the requested window timeslot size for ONU$_i$; W_i^k is the window timeslot size for ONU$_i$ at k-th cycle; and R_i^k is the requested window timeslot size from ONU$_i$ at k-th cycle.

This scheme can achieve higher bandwidth utilization; however, it may fail to fully utilize the bandwidth under non-uniform traffic. For example, one OLT manages N·ONUs in the EPON network. Among N·ONUs, just one ONU wishes to send the data to the OLT while the others remain in the idle state. In this case, the ONU can send data by using the maximum window timeslot size $W_{\max}$ in each cycle, where a cycle consists of $W_{\max}$, N guard times ($N \cdot G$), and N report times ($N \cdot R$). Therefore, we find the utilization is limited to

$$U = \frac{W_{\max}}{W_{\max} + N \cdot G + N \cdot R}. \tag{2}$$

This is because the OLT cannot grant more than $W_{\max}$ even if the other ONUs do not use their guaranteed maximum window timeslot size. Accordingly, if the number of idle ONUs per cycle increases, the unused window timeslot size increases, causing degradation of the bandwidth utilization by the upstream. To resolve these problems, we propose a new enhanced DBA with fairness scheme, which achieves high bandwidth utilization, low delay, low packet loss, and low queue occupancy. We propose a new enhanced dynamic bandwidth allocation algorithm with fairness called EFDBA to improve bandwidth utilization efficiently. The remainder of this paper is organized as follows. Section II introduces our proposed EFDBA mechanism. Performance evaluations are given in section III. Simulation results are given in section IV, and we conclude in section V.

II. Proposed EFDBA Algorithm

In this section, we present a new enhanced dynamic bandwidth allocation scheme with fairness, EFDBA. Fairness is achieved by making use of the unused window timeslot size from idle ONUs. Our proposed EFDBA scheme is similar to that proposed in [12]. However, we propose a fairness structure between ONUs.

We assume that the maximum cycle time, $C_{\max}$, is known when the OLT initializes the poll entry table using the allocated maximum window timeslot size, $W_{\max}$. In total, N ONUs are connected to one OLT, and the guard time is denoted by G. $W_{\max}$ is comprised of W_E and W_T, which are the ensured maximum window timeslot size to all ONUs and the tentative window timeslot size for ONUs, respectively.

First, we determine the maximum cycle time $C_{\max}$, using W_E, W_T, and G, where G provides protection against fluctuations of round-trip time (RTT) and the control message processing time of various ONUs. That is, we first define the maximum cycle time, consisting of W_E, W_T, and G. Within each cycle, the total ensured window timeslot size for ONUs is determined by $W_E = \sum_{i=0}^{N-1} T_{E,i}$, where $T_{E,i}$ is a reserved window timeslot size for ONU$_i$. In our paper, we assume that each ONU has the same reserved maximum window timeslot size. Therefore, we can express the total ensured window timeslot size per cycle as

$$W_E = N \cdot T_{E,i} \quad \forall i. \tag{3}$$

The tentative window timeslot size is defined as

$$W_T = C_{\max} - N \cdot T_{E,i} - N \cdot G. \tag{4}$$

Actually, W_T is an important factor in our scheme to efficiently allocate bandwidth to ONUs. That is, all ONUs are able to share the tentative window timeslot size from the OLT controller, which manages the tentative window timeslot. For example, when an ONU's request for a window timeslot size exceeds the reserved maximum window timeslot size, the OLT allocates the remaining tentative window timeslot size.

We can calculate the rest of the tentative window timeslot size (W_{TR}) using the past N-1 grants as $\{W_i\}_{i=0,1,2,\cdots,N-1}$. The k-th rest of the tentative window timeslot size for ONU$_i$ is derived by

$$W_{TR,i}^{k} = W_T - \sum_{j=(i-N+1) \bmod N}^{(i-1) \bmod N} \max(W_j - T_{E,j}, 0), \quad (5)$$

where $W_j - T_{E,j}$ is an over-grant size.

If $R_i \le T_{E,i}$, the requested window timeslot size from ONU$_i$ follows with a predetermined service level agreement, and the OLT grants the requested window timeslot size, which does not exceed the reserved maximum window timeslot size W_i by R_i.

If $R_i > T_{E,i}$, the requested window timeslot size exceeds the reserved maximum window timeslot size. The OLT controller starts to calculate a suitable window timeslot size in advance, disregarding the unused window timeslot size during the maximum cycle time, using a fairness weighting counter. Therefore, if enough window timeslots are unused by other ONUs, the OLT can allocate both the rest of the tentative window (W_{TR}) and the unused ensured window timeslot size (W_{E_unused}).

Depending on the traffic condition, $W_{TR,i}$ varies dynamically. If aggregated traffic is light-loaded, that is, $R_i \le T_{E,i}$, $W_{TR,i}$ becomes large. If it is over-loaded, that is, $R_i > T_{E,i} + W_{TR,i}$, $W_{TR,i}$ becomes almost zero. Large $W_{TR,i}$ induced by precedent light-loaded ONUs can be used to process busy ONU$_i$. As stated in [10], cycle time shrinkage and an increased guard time ratio is the main reason for low utilization under non-uniform traffic. Cycle time shrinkage can be prevented by $W_{TR,i}$ because busy ONUs can use remnant time left by precedent light-loaded ONUs. This contributes to improve the utilization under non-uniform traffic and reduces the delay time, packet loss, and queue size.

We can determine the total unused rest-of-window timeslot size ($W_{R,i}$) for ONU$_i$ per cycle as

$$W_{R,i} = W_{TR} + W_{E_unused}, \quad (6)$$

where W_{E_unused} is the unused ensured window timeslot size contributed by previous ONUs.

The unused ensured window timeslot size allocated to the previous (N-1)·ONUs is calculated as

$$W_{E_unused} = N \cdot T_{E,j} - \sum_{j=(i-N+1) \bmod N}^{(i-1) \bmod N} \max(T_{E,j} - W_j, 0). \quad (7)$$

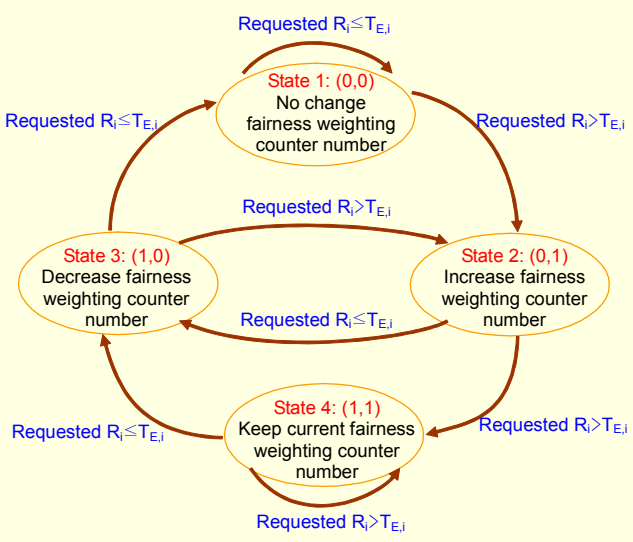


Fig. 2. State diagram of the fairness weighting counter in OLT system.

By using the EFDBA scheme, the (k+1)th granted window timeslot size that can be allocated for ONU$_i$ is determined as

$$W_i^{k+1} = \begin{cases} R_i^k & \text{if } R_i^k \le W_E, \\ \min(\{(1/R_{Counter,i}) \cdot (W_{R,i})\}, R_i^k) & \text{otherwise,} \end{cases} \quad (8)$$

where the $R_{Counter,i}$ is a fairness weighting counter that measures the number of ONUs that want to use W_R in the OLT to fairly allocate the unused rest-of-window timeslot size to ONUs in the early cycle period. In our paper, the fairness weighting counter is the most important factor to fairly enhance the performance of DBA to all ONUs. This fairness weighting counter is defined by four states: {(0, 0), (0, 1), (1, 0), (1, 1)}. Using these four states, we can decide when the fairness weighting counter number increases or decreases in the OLT. Figure 2 shows the state diagram of the fairness weighting counter in the OLT system.

An explanation of the fairness weighting counter process in the OLT follows.

The (0, 0) state denotes that the requested ONU, which is sent in the request message included with the requested window timeslot size, does not need to use W_R in the next cycle and that this ONU did not use W_R until this cycle. When the state of fairness weighting counter is (0, 0), the counter number in the OLT maintains the current state without increasing or decreasing. During this state, the granted window timeslot size that may be allocated for ONU$_i$ is R_i^k.

In the (0, 1) state, the requested ONU needs to use W_R, which means the requested window timeslot size from the ONU exceeds the maximum ensured window timeslot size. However, before receiving the request message in the OLT, the ONU did

not use W_R during the previous cycle. After checking the state information in the OLT, the counter controller has to increase the fairness counter number from 0 to 1. During this state, the granted window timeslot size that may be allocated for ONU$_i$ is determined as $\min((1/R_{counter,i})\cdot(W_{R,i}), R_i^k)$

The (1, 0) state means that W_R was used in the previous cycle, however the requested ONU does not need to use W_R. After checking the state information, the OLT counter controller has to decrease the fairness counter number. During this state, the granted window timeslot size that may be allocated for ONU$_i$ is R_i^k.

Finally, the (1, 1) state means that W_R was used in the previous cycle, and the requested ONU also needs to use W_R. Thus, the requested window timeslot size exceeds the maximum ensured window timeslot size in the next cycle. That is, during this state the OLT counter controller maintains the current counter number by continuously using W_R in the next cycle. Consequently, during the early cycle period we can fairly allocate the unused window timeslot size to ONUs that want to use the rest-of-window timeslot size (W_R).

Since ONUs are already using the rest-of-window timeslot size and new ONUs require use of the rest-of-window timeslot, we devised the concept of the fairness state to ensure an equitable sharing strategy, which moderates the number of cycle periods that result in unfairness. As soon as the OLT receives a request message that exceeds the ensured window size from a new ONU, the OLT can check the fairness state and update the fairness weighting counter to allocate the maximum window timeslot size.

This procedure repeats recursively until the W_R of all ONUs in the OLT's polling table converges to one. This new, efficient EFDBA scheme with fairness factor supports a proficient window timeslot size without the unused rest-of-window timeslot for ONUs. Therefore, the biggest advantage of EFDBA in comparison with conventional DBA algorithms is that it uses W_R between ONUs fairly after only a few cycles. This means that a few cycle periods quickly increase the overall utilization of bandwidth and the allocated window timeslot size to ONUs.

III. Performance Analysis of Steady State Fairness

In this section, we analyze the steady state fairness under the fairness weighting counter ($R_{counter,\ i}$). First, we assume that N ONUs are connected with one OLT. Among N ONUs, X ONUs want to use the rest-of-window timeslot size with a fairness weighting counter ($R_{counter,\ i}$). The OLT checks the fairness weighting counter to quickly allocate the rest-of-window timeslot.

If $R_{Counter,i} \neq 0$, the rest-of-window timeslot (W_R) is currently being used by some other ONUs. On the other hand, if $R_{counter,\ i} = 0$, W_R is not consumed by ONUs. To analyze the steady state fairness under excessive window timeslot size conditions for ONUs, we use the recursive formula of $W_{R,i}(k)$, which denotes the rest-of-window timeslot size, including the ensured window timeslot size, for ONUs at the k-th cycle. At the k-th cycle, $W_{R,i}$ is defined as

$$\begin{aligned} W_{R,\,i\neq 0}(k) &= R_{Counter,i}\cdot W_{R,i}(k-1)+(1-R_{Counter,i-1})W_{R,i-1}(k),\\ W_{R,\,i=0}(k) &= R_{Counter,i}\cdot W_{R,i}(k-1)+(1-R_{Counter,N-1})W_{R,N-1}(k-1). \end{aligned} \tag{9}$$

Therefore, the steady state value of $F(=(1/R_{Counter,i})\cdot(W_{R,i}))$ converges to

$$F=\frac{W_T}{\{(X-1)+(1/R_{Counter,i})\}} \qquad \forall i\,. \tag{10}$$

The utilization of the unused rest-of-window timeslot is calculated as

$$U_R=\frac{X}{\{(X-1)+(1/R_{Counter,i})\}} \qquad \forall i. \tag{11}$$

Figure 3 shows the convergence speed of $F(=(1/R_{Counter,i})\cdot(W_{R,i}))$ when 16 ONUs are over-loaded in both SLICT and our proposed EFDBA scheme.

Figures 3(a) and (b) show the results of SLICT with fairness weighting factors (α) of 0.8 and 0.9, respectively. These results indicate that when the total shared time is used by all 16 ONUs, the shared time could be fairly shared by 16 ONUs over many cycles. The results showing the required cycle time needed to use the shared time fairly in 16 ONUs indicate that smaller α values require a shorter cycle time. In the case of a large α value, more cycle time is required to use the shared time in all ONUs. Under the SLICT case, the α value should be enlarged to increase the utilization of the shared time; however, weak points arise concerning fairness. Therefore, a tradeoff exists between shared time utilization, with respect to the α value, and the fairness of an ONU that uses shared time.

Figure 3(c) is the result of our proposed EFDBA. It demonstrates that 16 ONUs are not required to wait through the cycle time before collectively sharing the unused rest-of-window timeslot ($W_{R,i}$) contributed from just one ONU. On the other hand, SLICT needs more than 65 cycles to establish fairness with $\alpha = 0.8$ and needs more than 150 cycles at $\alpha = 0.9$. However, under the proposed EFDBA, which allows use of the total unused rest-of-window timeslot, one cycle is sufficient to establish fairness and a higher utilization than SLICT, which needs to use the shared time commensurate with

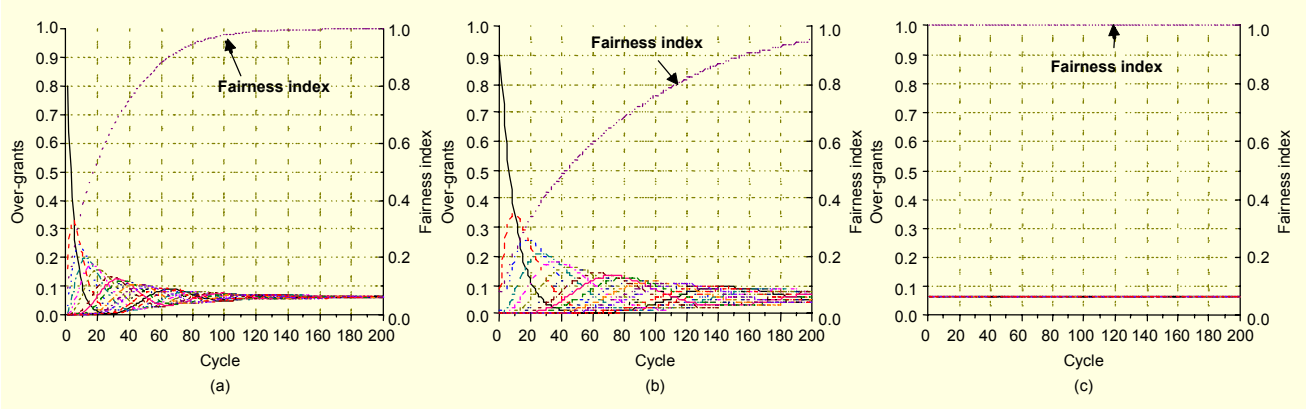


Fig. 3. Performance comparison of IPACT, SLICT, and EFDBA based on the traffic environment (from ONU_0 to ONU_3) shown in Table 2: (a) IPACT, (b) SLICT, and (c) EFDBA.

α values less than 1.

The convergence speed depends on $1/R_{counter,i}$, which effects one cycle period. This means that if we use $1/R_{counter,i}$ efficiently managed by OLT, the convergence speed rises quickly. That is, we could allocate the unused rest-of-window timeslot to ONUs that exceed the requested window timeslot size, after a few cycle periods. Consequently, some ONUs that wish to use the unused rest-of-window timeslot can fairly acquire the extra window in the next cycle.

IV. Simulation Results

In this section, we present simulation results to verify our analysis and demonstrate the performance of our proposed EFDBA scheme. We generate the self-similar traffic by Poisson-distributed sources, and we generate Ethernet packet frames distributed from 64 bytes to 1,518 bytes.

Table 1 shows simulation parameters. To observe the fairness performance of the three schemes, we make a simulation traffic scenario as in Table 2. In the scenario, ONU_0 to ONU_3 send traffic at 500 Mbps from 0 second to 20 seconds, and background traffic is contributed by ONU_4 to ONU_{15} as shown in Table 2.

Figure 4 shows the throughput when 1 Gbps is equally shared by N ONUs, while $(16 - N)$ ONUs are idle under various kinds of background traffic. Comparing the performance results of EFDBA, IPACT, and SLICT, the proposed EFDBA scheme achieves the best throughput.

Figures 5(a) and (b) show the fairness index of 4 ONUs (from ONU_0 to ONU_3) between 10 and 15 seconds and normalized total throughput in EFDBA, IPACT, and SLICT, respectively.

In IPACT and EFDBA, the fairness index maintains a value close to 1. However, in SLICT, the fairness index drops as the shared timeslot size changes. Between IPACT and EFDBA,

Table 1. Simulation parameters.

Parameter	Value
Number of ONUs (N)	16
Link rate of EPON (BW)	1 Gbps
Maximum cycle time (C_{MAX})	2 ms
Guard time (G)	5 μs
Reserved timeslot (T_E)	60 μs
Ensured timeslot (W_E)	960 μs
Tentative timeslot (W_T)	960 μs
Fairness factor in SLICT (α_i)	0.9
Distance from OLT to ONUs	10 km
Queue size	10 Mbyte
ONU input	Self-similar traffic

Table 2. Simulation traffic scenario.

Time (s)	ONU_0-ONU_3	ONU_4-ONU_7	ONU_8-ONU_{15}
0 to 5	500 Mbps	500 Mbps	Null
5 to 10	500 Mbps	Null	Null
10 to 15	500 Mbps	50 Mbps	Null
15 to 20	500 Mbps	10 Mbps	Null

the existing gate scheduling in IPACT may fail to guarantee fairness; however, the proposed EFDBA guarantees fairness.

Figure 5(b) shows the upstream capacity of test ONUs with various kinds of background traffic. Upstream capacity reflects how much bandwidth the test ONU can use when background traffic exists. Therefore, in normalized total throughput, our proposed EFDBA scheme can fairly grant a longer window timeslot to ONUs by using a fairness weighting counter and making bandwidth allocation decisions considering the unused

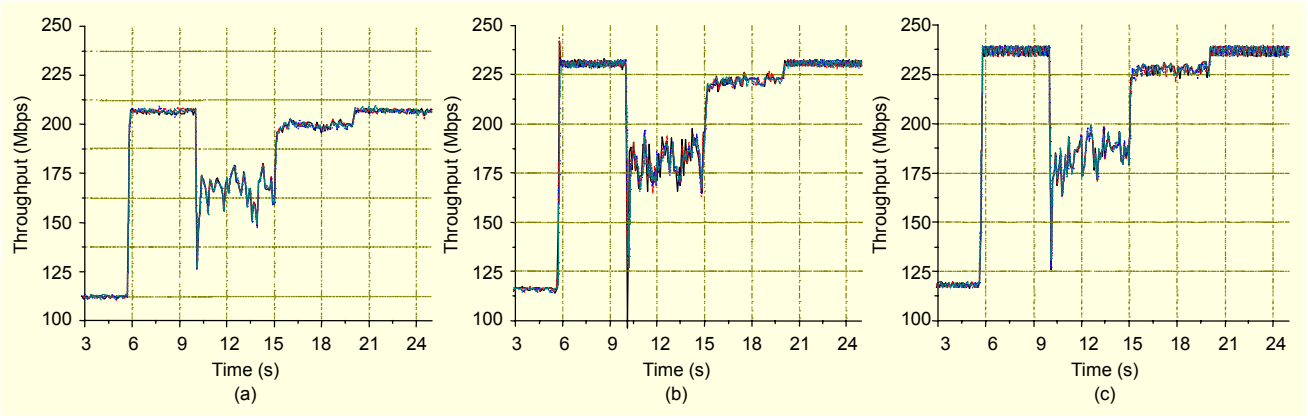


Fig. 4. Convergence speed in SLICT to use shared time when (a) α = 0.8 and X=16, (b) α = 0.9 and X=16, and (c) convergence speed in EFDBA to use total unused window timeslot when X=16.

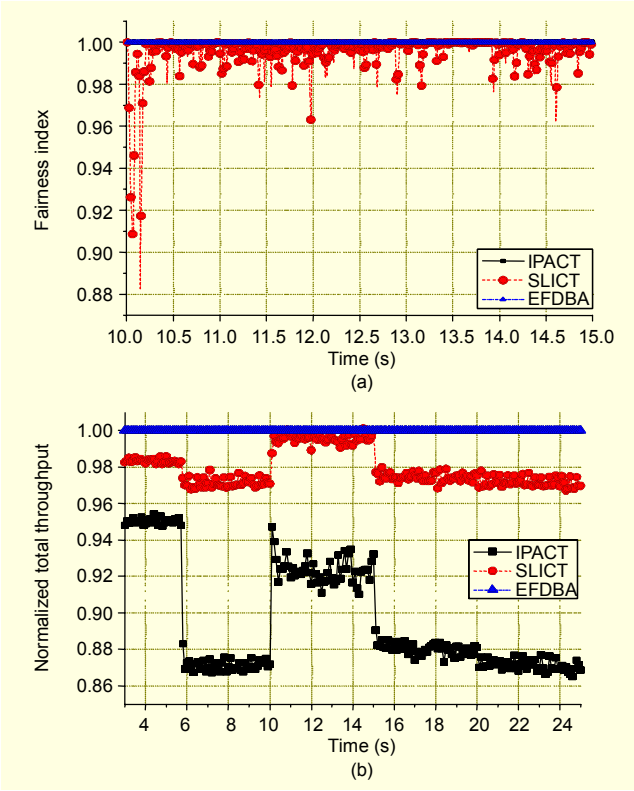


Fig. 5. (a) Fairness index comparisons and (b) normalized total throughput of IPACT, SLICT, and EFDBA.

rest-of-window timeslots of other ONUs. Therefore, we can always achieve full utilization throughput regardless of the network load.

V. Conclusion

In this paper, we focused on the low bandwidth utilization problem of conventional DBA schemes under non-uniform traffic, which lack fairness. To solve this problem, we proposed a new enhanced dynamic bandwidth allocation scheme with fairness, called EFDBA which provides high efficient resource utilization by reducing the unused remaining bandwidth. Based on our analysis and simulation results, our EFDBA scheme achieves a significant improvement in utilization throughput, convergence speed, and fairness under various traffic conditions, especially non-uniform traffic.

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