Fuzzy Logic Embedded in Prediction-Based DBA for Differentiated Services on EPONs

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Abstract

A *Fuzzy Prediction-based Dynamic Bandwidth Allocation* (*FPDBA*) algorithm is proposed to enhance the differentiated services for EPONs based on the *Prediction-based Fair Excessive Bandwidth Reallocation* (*PFEBR*) in our previous work. The PFEBR proposed an *Early-DBA* mechanism which improves prediction accuracy by delaying report messages of unstable traffic ONUs and assign estimation credit to predict the traffic arrival during waiting time. However, delaying one report message will increase a guard time in one transmission cycle, how many report messages should be delayed and what is the optimal linear estimation credit are important issues. Both *Fuzzy Unstable Degree List Controller* (*FUDLC*) and *Fuzzy Credit Estimator* (*FCE*) mechanisms are incorporated to improve the prediction accuracy and enhance the system performance for differentiated services. The FUDLC chooses the second traffic variance and the mean traffic variance of ONUs as input linguistic variables to determine the optimal number of ONUs in the *unstable degree list*. In addition, the FCE chooses the degree of traffic variance and the degree of waiting time among ONUs as input linguistic variables for the credit estimation, so that the request bandwidth for the next cycle can be predicted more precisely. Simulation results show that the proposed FPDBA algorithm outperforms the efficient bandwidth allocation algorithm (EAA) and DBA with multiple services algorithm (DBAM) in terms of wasted bandwidth, gain ratio of bandwidth, throughput, downlink available bandwidth, average end-to-end delay and average queue length, especial in heavy traffic load.

Key Words: FPDBA, Differentiated Services, EPON, PFEBR, FUDLC, FCE, EAA, DBAM

1. Introduction

With the expansion of services offered over the internet, the backbone networks have experienced tremendous growth in bandwidth capacity to meet the ever-increasing bandwidth demand of network users, such as interactive games, video conference, high-definition television (HDTV) and other high-speed services. Compared with the current access network technologies, the passive optical network (PON) technologies are expected as one promising solution for the full service access network because optical fiber can satisfy the increasing bandwidth demand. The PON architecture, shown in Figure 1, comprises of a centralized optical line terminal (OLT), splitters, and connects a group of associated optical network units (ONUs) over point-to-multipoint topologies to deliver broadband packet and reduce cost relative to maintenance and power.

Two standard organizations, ITU-T (International

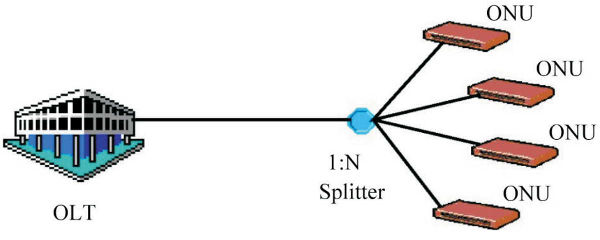

Figure 1. Tree-based PON topology.

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Telecommunications Union Standardization Sector) and IEEE (Institute of Electrical and Electronics Engineers), have led the discussion of PON specifications. In ITU-T, a series of ATM-based Broadband PON (i.e. ATM-PON, BPON and GPON), have been recommended [1]. Furthermore, Ethernet PON (EPON) has been discussed in IEEE 802.3ah as one of the extensions of Gigabit-Ethernet [2]. The main difference between EPON and ATM-based Broadband PON is that EPON carries all data encapsulated according to the IEEE 802.3 Ethernet frame format between the OLT and ONUs. Recently, EPON have gained more attention from industry due to the convergence of low-cost Ethernet equipment and fiber infrastructure.

The EPON provides bi-directional transmission. In the downstream direction, EPON broadcasts control messages from the OLT to each ONU through the entire bandwidth of one wavelength. In the upstream direction, EPON utilizes time division multiple access (TDMA) coupled with multi-point control protocol (MPCP) mechanism to avoid collision [3]. The MPCP involves both GATE and REPORT messages. The OLT allocates upstream bandwidth to each ONU by sending GATE messages with the form of a 64-byte MAC control frames. GATE messages contain a timestamp and granted time slots which represent the periods that ONU can transmit data. Each ONU may send REPORT messages about the queue state to the OLT, so that the OLT can allocate the upstream bandwidth and time slots to each ONU accordingly. With the multiple ONUs share the same upstream bandwidth to transmit data on the EPON, any data collision will cause longer end-to-end delay and deteriorate system performance. Bandwidth allocation has become a prominent concern of research on the EPON, especially with the enormous of bandwidth demand and critical applications.

The bandwidth allocation schemes can be divided into two categories: *fixed bandwidth allocation* (*FBA*) and *dynamic bandwidth allocation* (*DBA*). The straightforward concept of FBA is pre-assigned a fixed time slot to each ONU transmits its data once to OLT. The FBA is simple to implement, however, an ONU will occupy the upstream channel for its assigned time slot even if there is no frame to transmit, thus resulting in long delay for all the Ethernet frames buffered in other ONUs. An alternative method, DBA, assigns bandwidth dynamically using queue state information that is received from ONUs. Therefore, DBA schemes can provide more efficient bandwidth allocation for each ONUs to share the network resources.

DBA schemes can be classified into non-predictive and predictive. In the non-predictive schemes, each ONU experiences a waiting time from sending the REPORT message to sending the buffered frames. Each ONU only reports the already buffered frames to the OLT. Therefore, frames that arrive during the waiting time have to be delayed to the next transmission cycle even if the upstream channel is in lightly-loaded traffic. The predictive schemes take the traffic arrival during the waiting time into consideration. When the OLT allocates the request bandwidth to ONUs, it adds a credit into the requirement of each ONU. The incoming traffic during waiting time is expected to be transmitted (or partially transmitted) within the current time slot. Furthermore, the predictive schemes are studied in order to decrease packet delay and allocate more bandwidth efficiently. Accurate traffic predictor is required to avoid over-estimation or under-estimation, which will result in longer packet delay to degrade the network performance.

The prediction-based fair excessive bandwidth reallocation (PFEBR) algorithm [3] is our previous research which has been developed to reduce idle period and improve prediction accuracy. The PFEBR arranges the sequence of transmitting REPORT messages to OLT by delaying some of unstable traffic ONUs. Delaying one of unstable traffic ONUs will increase a guard time in one transmission cycle, and what is the optimal number of unstable traffic ONUs will be delayed to transmit REPORT messages in one transmission cycle are important issues. The estimation credit in the PFEBR can be divided into three levels, which enhance more prediction accuracy than the fixed estimation credit value of the DBAM. However, if the estimation credit of the PFEBR could be determined according to the traffic variance, it will achieve more precise bandwidth allocation and prediction accuracy. In this paper, the f*uzzy unstable degree list control* (*FUDLC*) is adopted to dynamically adjust the number of unstable traffic ONUs which is delayed to transmit REPORT messages according to the traffic variance of ONUs in each transmission cycle. Furthermore, the *fuzzy credit estimator* (*FCE*) is proposed to determine the values of estimation credit according to the traffic variance and the variable waiting time. The simulation results show that the proposed FPDBA algorithm embedded with FUDLC and FCE mechanisms outperforms the well-known DBA algorithms in terms of wasted bandwidth, throughput, downlink available bandwidth, average end-to-end delay and average queue length.

The rest of this paper is organized as follows. Section 2 describes the related work of DBA on EPON. Section 3 proposes the FPDBA algorithm which the FUDLC and FCE mechanisms are incorporated to improve prediction accuracy. The performance of FPDBA algorithm is compared with other methodologies in the Section 4. Section 5 draws conclusions.

2. Related Work

The dynamic bandwidth allocation (DBA) is essential to an efficient EPON network and a key requirement for provisioning in business and residential deployments. Each ONU is assigned guaranteed bandwidth in proportion to its service level agreement (SLA) to support Quality-of-Service (QoS) in the DBA. In the limited bandwidth allocation (LBA) [4], the time slot length of each ONU is upper bounded by the maximum time slot length, $B_{\max}$, which could be specified by the SLA. When the reported queue size is less than $B_{\max}$, the OLT grants the requested bandwidth; otherwise, $B_{\max}$ is granted. The drawback of LBA is that no more bandwidth granted to ONUs that already assigned a guaranteed bandwidth $B_{\max}$, even though other ONUs have excessive bandwidth. The feature of LBA has poor utilization for the upstream bandwidth and restricts aggressive competition for the upstream bandwidth, especially under non-uniform traffic [5].

For every transmission cycle, each ONU requests bandwidth corresponding to its total backlog. If the requested bandwidth is smaller than the guaranteed bandwidth, the excess bandwidth is pooled together with the excess bandwidth from all other lightly-loaded ONUs whose requested bandwidth is less than their guaranteed bandwidth. In the efficient bandwidth allocation algorithm (EAA) [6,7], it redistributes the available bandwidth to heavily-loaded ONUs in proportion to each request and results in better performance in terms of packet delay. However, the drawbacks of excessive bandwidth reallocation are unfairness and excessive bandwidth allocated to ONUs than that requested. The DBA with multiple services (DBAM) is a prediction-based LBA that executes prediction according to the linear estimation credit [8]. The linear estimation credit of each ONU is based on the ratio of the ONU$_i$ waiting time (i.e. $t_2 - t_1$) over the time length of current interval (i.e. $t_2 - t_0$), which is shown in Figure 2. The OLT allocates the time slots for multiple services among the ONUs according to each bandwidth requirements and the SLA limits. In fact, the packet delay will be improved by the DBAM in uniform traffic flows. However, the performance is deteriorated in non-uniform traffic flows due to the prediction model with serious prediction inaccuracy in the DBAM for some ONUs have high variations in traffic load.

The PFEBR [3] executes the DBA scheme after the REPORT messages from unstable traffic ONUs are received at the end of ONU$_{N-1}$, instead of ONU$_N$ in the traditional DBA mechanism shown in Figure 3. The opera-

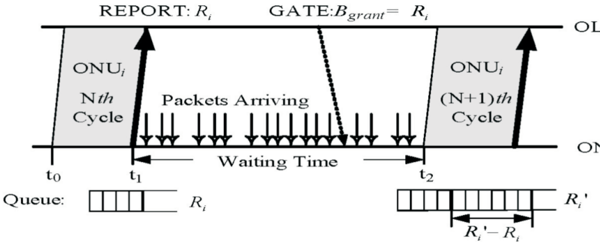

Figure 2. Queue state between waiting time.

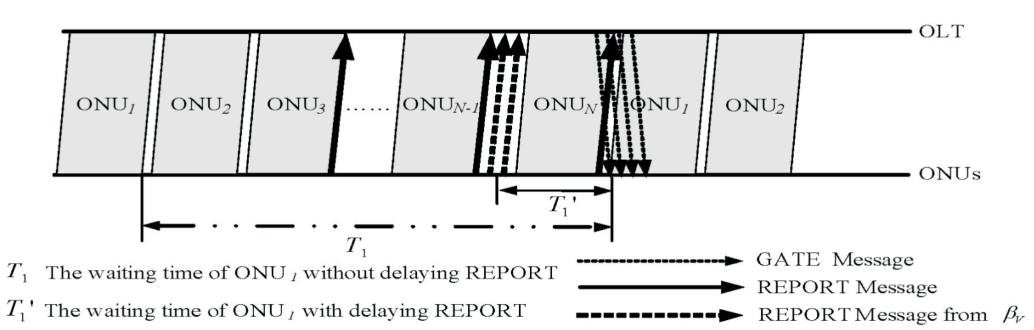

Figure 3. *E-DBA* mechanism of the PFEBR.

tion reduces the idle period in the traditional DBA mechanism and gathers more fresh information of unstable traffic ONUs to have more accurate prediction in the next cycle. Additionally, the bandwidth is allocated to each ONU in the next cycle is based on the unstable degree list. The unstable degree list is calculated using variance of historical traffic and sorted in decreasing order of all ONUs. The DBA mechanism of the PFEBR will alleviate traffic variance by shortening waiting time before transmitting data for unstable traffic ONUs and keep prediction more accurate. However, delaying one of unstable traffic ONUs will increase a guard time in one transmission cycle. The more guard time will cause more packet delay and deteriorate system performance. The number of unstable traffic ONUs in the *unstable degree list* is defined as one-eighth in the PFEBR, however, the value is not optimal.

Furthermore, the PFEBR predicts the traffic bandwidth, $R^c_{i,n+1}$ is needed for differentiated traffic classes of all ONUs is defined as follows:

$$R^c_{i,n+1} = (1+\alpha)B^c_{i,n}\ , \quad c \in \{EF, AF, BE\}$$

where $B^c_{i,n}$ is the requested bandwidth of ONU$_i$ in the n*th* cycle, and α is the linear estimation credit which is assumed the same for three types of traffic. If the ONU$_i$ belongs to unstable traffic ONUs, then α is 0. If the traffic variance of ONU$_i$ is larger than traffic mean variance and does not belong to unstable traffic ONUs, the α is $0.5 \times T^W_{i,n} / T_{i,n}$, where $T^W_{i,n}$ is the waiting time of ONU$_i$ and $T_{i,n}$ is the time length of current interval (i.e. $t_2 - t_0$); which is shown in Figure 2, otherwise, the α is $T^W_{i,n} / T_{i,n}$. The drawback of the PFEBR is that only three types of linear estimation credit are considered, and this results in imprecise prediction. In order to predict the traffic of ONUs smoothly, the FPDBA is proposed to determine the linear estimation credit according to the traffic variance and the variable waiting time.

3. Proposed FPDBA Algorithm

The *Fuzzy Prediction-based Dynamic Bandwidth Allocation* (*FPDBA*) algorithm is proposed in this section, which two mechanisms based on Fuzzy Set Theory [9, 10], *Fuzzy Unstable Degree List Control* (*FUDLC*) and *Fuzzy Credit Estimator* (*FCE*) are incorporated in the *Prediction-based Fair Excessive Bandwidth Reallocation* (*PFEBR*) algorithm [3]. The membership function of FUDLC mechanism depends on the second traffic variance and the mean traffic variance of ONUs. The membership function of FCE mechanism depends on the degree of ONUs traffic variance and the degree of waiting time. Three differentiated service classes are considered in this paper: expedite forwarding (EF) with the highest priority for strictly delay sensitive services that is typically constant bit rate (CBR) such as voice transmission, assured forwarding (AF) with medium priority for services of non delay sensitive variable bit rate (VBR) services such as video stream, and best effort (BE) with the lowest priority for delay tolerable services which include web browsing, background file transfer and e-mail applications. The definition of parameters is summarized in Table 1 and the flowchart of the FPDBA is shown in Figure 4.

Table 1. The Definition of Parameters

N_H	Number of historical REPORT messages recorded
V_i	The traffic variance of ONU$_i$
$\bar{V}$	The traffic mean variance of ONUs
β_V	The set of ONUs with higher traffic variance in unstable degree list
T_{cycle}	Maximum cycle time in each cycle
N	Number of ONUs in the system
$C_{capacity}$	Link capacity of OLT (bits/sec)
$B^c_{i,n}$	Requested BW of ONU$_i$ in the n*th* cycle, where $c \in \{EF, AF, BE\}$
$R^c_{i,n}$	Requested BW of ONU$_i$ after prediction in the n*th* cycle, where $c \in \{EF, AF, BE\}$
S^c_i	Guaranteed BW from the SLA in ONU$_i$, where $c \in \{EF, AF, BE\}$
λ	The ratio of ONUs in β_V to N, which is determined by the FUDLC
α	Linear estimation credit, which is determined by the FCE
$G^c_{i,n+1}$	Granted upload BW of ONU$_i$ in the (n+1)*th* cycle, where $c \in \{EF, AF, BE\}$

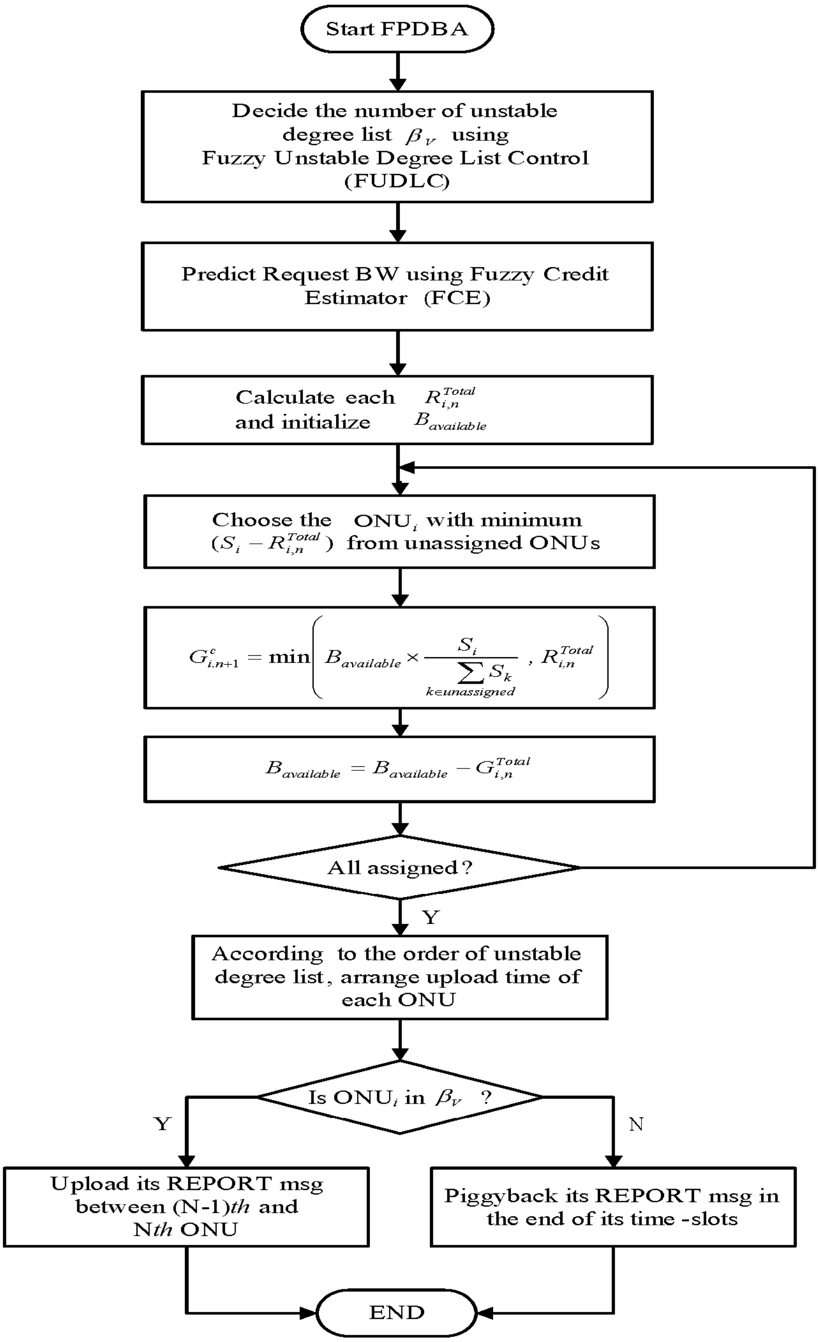

Figure 4. The flowchart of FPDBA.

3.1 Fuzzy Unstable Degree List Control (FUDLC)

The FUDLC calculates the traffic variance of each ONU based on the historical traffic required, and the traffic variance of each ONU is sorted in a decreasing order to obtain the unstable degree list. The traffic variance of ONU_i, V_i, can be expressed as follows:

$$V_i = \frac{1}{N_H}\sum_{n\in historical\ cycle}(B_{i,n} - \overline{B_i})^2 \qquad (1)$$

where $B_{i,n}$ is the requested bandwidth of differentiated traffics of ONU_i in the n*th* cycle, $\overline{B_i}$ is the mean bandwidth of historical traffic requested of ONU_i, i.e. $\overline{B_i} = \frac{1}{N_H}\sum_{n=1}^{N_H} B_{i,n}$, and N_H is the number of historical REPORT messages piggybacked.

After collecting all REPORT message and calculating the traffic variance of each ONU, the FUDLC is initiated to adjust the number of ONUs in β_V based on the second traffic variance (V_{Var}) and mean traffic variance of ONUs dynamically. The β_V is denoted as a set of ONUs with higher traffic variance in unstable degree list which is equal to $\lambda \cdot N$, where λ is the ratio of ONUs in β_v to total number of ONUs. The second traffic variance (V_{Var}) can be defined as follows:

$$V_{Var} = \frac{1}{N}\sum_{i=1}^{N}(V_i - \overline{V})^2 \tag{2}$$

where $\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i$ and the values of V_{Var} and $\overline{V}$ are normalized to the range [0, 1] based on the equations (3) and (4):

$$V_{Var} = \frac{V_{Var,n} - Min(V_{Var,N_H})}{Max(V_{Var,N_H}) - Min(V_{Var,N_H})} \tag{3}$$

$$\overline{V} = \frac{\overline{V_n} - Min(\overline{V_{N_H}})}{Max(\overline{V_{N_H}}) - Min(\overline{V_{N_H}})} \tag{4}$$

where $V_{Var,n}$ is the second traffic variance of n*th* cycle, V_{Var,N_H} is the second traffic variance of historical cycle, $\overline{V_n}$ is the mean traffic variance of n*th* cycle and $\overline{V_{N_H}}$ is the mean traffic variance of historical cycle.

Fuzzification is the process that translates the real number inputs of each feedback into linguistic terms. For the second traffic variance (V_{Var}) of ONUs in each transmission cycle, three linguistic terms are defined as $U_{V_{Var}}^{m}$ = {Low, Medium, High}, where m = (1, 2, 3), and the corresponding membership function shown in Figure 5. The fuzzy set for each membership function is expressed as follows:

$$F_{low}(x) = \begin{cases} 1 & , \quad x < 18\% \\ \dfrac{20-50x}{11} & , \quad 18\% \le x \le 40\% \end{cases}$$

$$F_{medium}(x) = \begin{cases} \dfrac{50x-15}{11} & , \quad 30\% \le x < 52\% \\ \dfrac{69\text{-}100x}{17} & , \quad 52\% \le x \le 69\% \end{cases}$$

$$F_{high}(x) = \begin{cases} \dfrac{100x-66}{21} & , \quad 66\% \le x < 87\% \\ 1 & , \quad x \ge 87\% \end{cases}$$

For the mean traffic variance of ONUs, three linguistic terms are defined as $U_{\bar{V}}^{m}$ = {Low, Medium, High}, where m = (1, 2, 3) with corresponding membership function is the same as the membership function of the V_{Var} which is shown in Figure 5.

The FUDLC infers the fuzzy set of β_v using if-then rules based on the second traffic variance of ONUs, V_{Var}, and the mean traffic variance of ONUs, $\overline{V}$. The fuzzy rule is shown in Table 2.

3.2 Fuzzy Prediction Scheme Based on the Unstable Degree List

After arranging the upload sequence of all ONUs from the unstable degree list, the *fuzzy credit estimator* (*FCE*) is initiated to adjust estimation credit dynamically, which is based on the degree of traffic variance and the degree of waiting time.

3.2.1 Degree of Traffic Variance

Degree of traffic variance (V_{degree}) is defined as the traffic variance of ONUs. The more unstable traffic of ONUs, the higher degree of traffic variance is. The degree of traffic variance of ONU$_i$, V_{degree}, can be expressed as

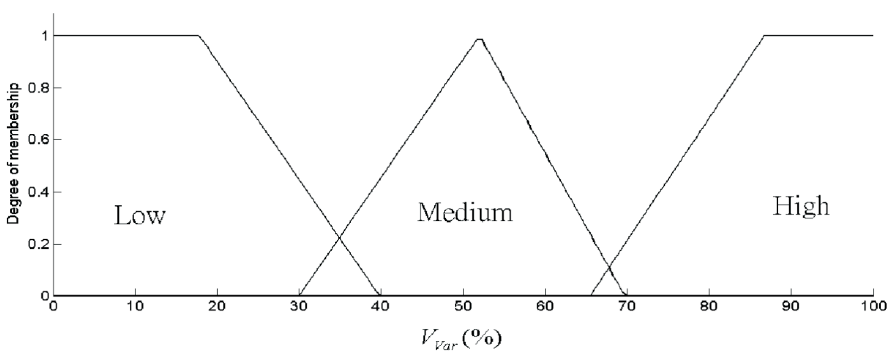

Figure 5. Membership function of V_{Var}.

Table 2. Values of λ

	V_{Var}		$\bar{V}$		λ
If	High	and	High	Then	0.9
If	Medium	and	High	Then	0.8
If	Low	and	High	Then	0.7
If	High	and	Medium	Then	0.6
If	Medium	and	Medium	Then	0.5
If	Low	and	Medium	Then	0.4
If	High	and	Low	Then	0.3
If	Medium	and	Low	Then	0.2
If	Low	and	Low	Then	0.1

$$V_{\deg ree} = \frac{V_i}{\overline{B_i}}$$

where V_i is the traffic variance of ONU$_i$, $\overline{B_i}$ is the mean of the $B_{i,n}$, i.e. $\overline{B_i} = \frac{1}{N_H}\sum_{n=1}^{N_H} B_{i,n}$, and N_H is the number of historical REPORT messages piggybacked. The value of V_{degree} is normalized to the range [0, 1] based on the equation (5):

$$V_{\deg ree} = \frac{V_{\deg ree,n} - Min(V_{\deg ree,N_H})}{Max(V_{\deg ree,N_H}) - Min(V_{\deg ree,N_H})} \quad (5)$$

where $V_{degree,n}$ is the degree of traffic variance of ONU$_i$ in n*th* cycle, and V_{degree,N_H} is the degree of traffic variance of historical cycle.

The membership function of the V_{degree} is shown in Figure 6, and three linguistic terms are defined as $U^m_{V_{\deg ree}}$ = {Low, Medium, High}, where m = (1, 2, 3). The fuzzy set for each membership function is expressed as follows:

$$F_{low}(x) = \begin{cases} 1 & , \quad x < 20\% \\ \dfrac{11-25x}{6} & , \quad 20\% \le x \le 44\% \end{cases}$$

$$F_{medium}(x) = \begin{cases} \dfrac{20x-7}{3} & , \quad 35\% \le x < 50\% \\ \dfrac{13\text{-}20x}{3} & , \quad 50\% \le x \le 65\% \end{cases}$$

$$F_{high}(x) = \begin{cases} 5x-3 & , \quad 60\% \le x < 80\% \\ 1 & , \quad x \ge 80\% \end{cases}$$

3.2.2 Degree of Waiting Time

The degree of waiting time, $T^W_{\deg ree}$, can be expressed as $T^W_{i,n} \,/\, T_{i,n}$, where $T^W_{i,n}$ is the waiting time of ONU$_i$, i.e. $T^W_{i,n} = \sum_{k \in ONU_s \text{ in the interval of ONU}_i} Min(R_k^{Total}, S_k)$, where R_k^{Total} is the sum of differentiated traffics after being predicted, S_k is the sum of S_k^c for three differentiated traffics, and the minimum guaranteed time slots for differentiated traffic determine by service level agreement (SLA).

The membership function of the $T^W_{\deg ree}$ is shown in Figure 7, and three linguistic terms are defined as $U^m_{T^w_{\deg ree}}$ = {Low, Medium, High}, where m = (1, 2, 3). The fuzzy set for each membership function is expressed as follows:

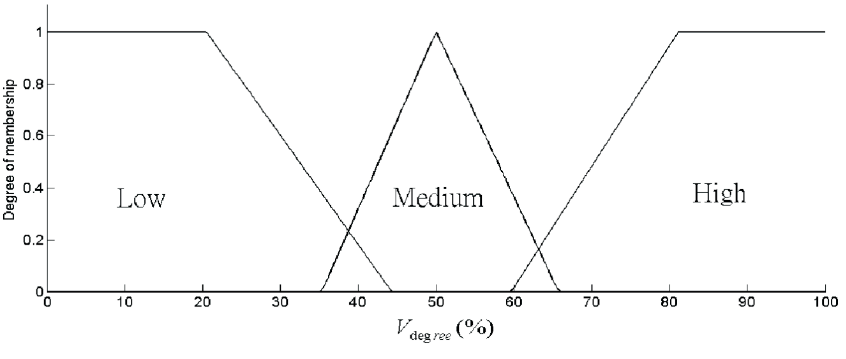

Figure 6. Membership function of V_{degree}.

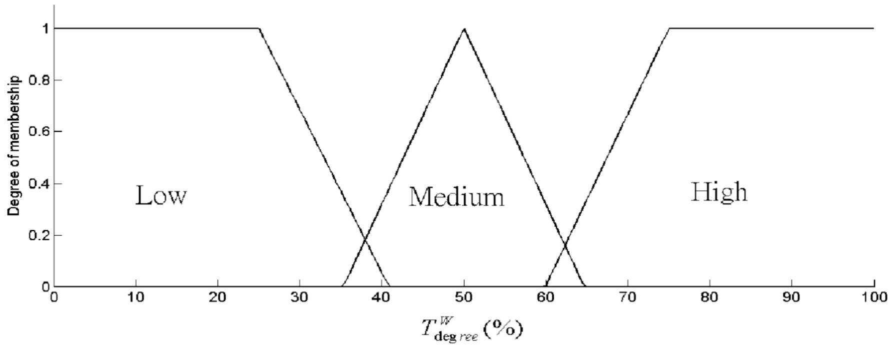

Figure 7. Membership function of $T^{w}_{\deg ree}$.

$$F_{low}(x)=\begin{cases}1 & , \quad x<25\% \\ \dfrac{41-100x}{16} & , \quad 25\% \le x \le 41\%\end{cases}$$

$$F_{medium}(x)=\begin{cases}\dfrac{20x-7}{3} & , \quad 35\% \le x < 50\% \\ \dfrac{13\text{-}20x}{3} & , \quad 50\% \le x \le 65\%\end{cases}$$

$$F_{high}(x)=\begin{cases}\dfrac{20x}{3}-4 & , \quad 60\% \le x < 75\% \\ 1 & , \quad x \ge 75\%\end{cases}$$

In general, the estimation credit increases when the V_{degree} is low and the $T^{W}_{\deg ree}$ is high. The FCE infers the fuzzy set of estimation credit using if-then rules based on the traffic variance degree of ONUs, V_{degree}, and the waiting time degree of ONUs, $T^{W}_{\deg ree}$. The fuzzy rule is shown in Table 3, and α is the conclusion.

After setting the estimation credit using FCE, the predicted request, $R^{c}_{i,n+1}$, for three differentiated traffic classes of all ONUs is defined as follows:

$$\begin{cases}R^{EF}_{i,n} \quad = B^{EF}_{i,n} \\ R^{c}_{i,n+1} = (1+\alpha)B^{c}_{i,n} \quad , \quad c \in \{AF, BE\}\end{cases} \tag{6}$$

where $B^{c}_{i,n}$ is the requested bandwidth of ONU$_i$ in the n*th* cycle for two differentiated traffic classes $c \in \{AF, BE\}$, and α is the linear estimation credit modified from the PFEBR [3]. To achieve a better performance for time critical applications that have a constant bit rate (CBR), such as EF traffic, it would be preferable to assign the CBR bandwidth to the ONUs according to the rate of these applications.

3.3 Fair Excessive Bandwidth Allocation

After finishing prediction bandwidth needed for each ONU, the FPDBA algorithm executes the fair bandwidth allocation algorithm modified from the PFEBR [3] to assign uplink bandwidth to each ONU. The operation of fair bandwidth allocation is described as follows.

First, calculate $R^{Total}_{i,n}$ of all ONUs and initialize the available bandwidth, $B_{available}$, can be expressed as

Table 3. Values of α

	V_{degree}		$T^{W}_{\deg ree}$		α
If	Low	and	High	Then	0.9
If	Low	and	Mid	Then	0.8
If	Low	and	Low	Then	0.7
If	Mid	and	High	Then	0.6
If	Mid	and	Mid	Then	0.5
If	Mid	and	Low	Then	0.4
If	High	and	High	Then	0.3
If	High	and	Mid	Then	0.2
If	High	and	Low	Then	0.1

$$B_{available} = C_{capacity} \times (T_{cycle} - N \cdot g - N_v \cdot g) - N \times 512 \quad (7)$$

where $C_{capacity}$ is the OLT link capacity (bits/sec), T_{cycle} is the maximum cycle time, g is the guard time, N is the number of ONUs and N_V is the number of ONUs in β_V with control message length 512 bits (64 bytes).

Then, select the ONU$_i$ with the maximal residue bandwidth, i.e. $\max(S_i - R^{Total}_{i,n})$, from unassigned ONUs. The granted bandwidth for ONU$_i$, $G^{Total}_{i,n+1}$, in the next cycle is given as follows:

$$G^{Total}_{i,n+1} = \min\left(B_{available} \times \frac{S_i}{\sum_{k \in unassigned} S_k}, R^{Total}_{i,n} \right) \quad (8)$$

where $R^{Total}_{i,n}$ is the sum of differentiated traffics after being predicted of ONU$_i$ in the n*th* cycle, $\frac{S_i}{\sum_{k \in unassigned} S_k}$ is the proportion of ONU$_i$ which is the granted bandwidth from available bandwidth, $B_{available}$. Furthermore, the granted bandwidth for EF, AF and BE classes are described as follows:

$$\begin{cases} G^{EF}_{i,n+1} = R^{EF}_{i,n} \\ G^{AF}_{i,n+1} = \min(G^{Total}_{i,n+1} - G^{EF}_{i,n+1}, R^{AF}_{i,n}) \\ G^{BE}_{i,n+1} = G^{Total}_{i,n+1} - G^{EF}_{i,n+1} - G^{AF}_{i,n+1} \end{cases}$$

The process $B_{available} = B_{available} - G^{Total}_{i,n+1}$ continues until all ONUs has been assigned. Finally, the FPDBA arranges the upload sequence and report time of each ONU by unstable degree list.

4. Performance Evaluation

The performance evaluation is studied using the OPNET simulation tool and the MATLAB fuzzy tools. The buffer of ONUs is assumed infinite. The service policy is in first-in first-out discipline. For the traffic model, an extensive study shows that most network traffic can be characterized by self-similarity and long-range dependence (LRD) [11]. Three differentiated traffic classes are considered in this thesis. Class EF with high-priority traffic is modeled using a Poisson distribution and packet size is fixed to 70 bytes [4]. Classes AF and BE with bursty traffic are modeled with the Hurst parameter of 0.7 [8], and packet sizes are uniformly distributed between 64 and 1518 bytes. The traffic profile is as follows: 20% of the total generated traffic is EF traffic, and the remaining 80% equally distributed between AF and BE traffic [7,12]. The simulation scenario is summarized in Table 4.

The performance of the *FPDBA* is compared with other methodologies, PFEBR [3], DBAM [8] and EAA [6] in terms of wasted bandwidth, gain ratio of bandwidth, throughput, downlink data available bandwidth, average end-to-end delay and average queue length.

4.1 Wasted Bandwidth and Gain Ratio of Bandwidth

Imprecise bandwidth allocation means that the OLT allocate too much or too less bandwidth than the requested bandwidth to ONUs. The wasted bandwidth can be defined as allocating too much bandwidth to ONUs. The *gain ratio of bandwidth* is defined as gain (in %) on the average wasted bandwidth of FPDBA and PFEBR algorithms compared with the DBAM, respectively. It is calculated as *Gain - ratio - of Bandwidth* = $\frac{Bandwidth^{\mathrm{waste}}_{\mathrm{DBAM}} - Bandwidth^{\mathrm{waste}}_{\mathrm{FPDBA(PFEBR)}}}{Bandwidth^{\mathrm{waste}}_{\mathrm{DBAM}}}$.

Figure 8 compares the wasted bandwidth and gain ratio of bandwidth among the proposed FPDBA, PFEBR and DBAM. The wasted bandwidth problem is not considered in the EAA because no prediction mechanism is used.

The wasted bandwidth is increased when the traffic load is light and decreased when the traffic load exceeding 30% to 40%, shown in Figure 8(a). The reason is that the excessive bandwidth can be allocated from lightly-loaded ONUs is decreased when traffic load exceeds 40%. However, the FPDBA has least wasted bandwidth, even though no more excessive bandwidth can be allocated when traffic load exceeds 70%.

Table 4. Simulation Scenario

Number of ONUs in the system	32
Upstream/downstream link capacity	1 Gbps
OLT-ONU distance (uniform)	10–20 km
Maximum transmission cycle time	2 ms
Guard time	5 μs
Computation time of DBA	10 μs
Control message length	0.512 μs (= 64 bytes)

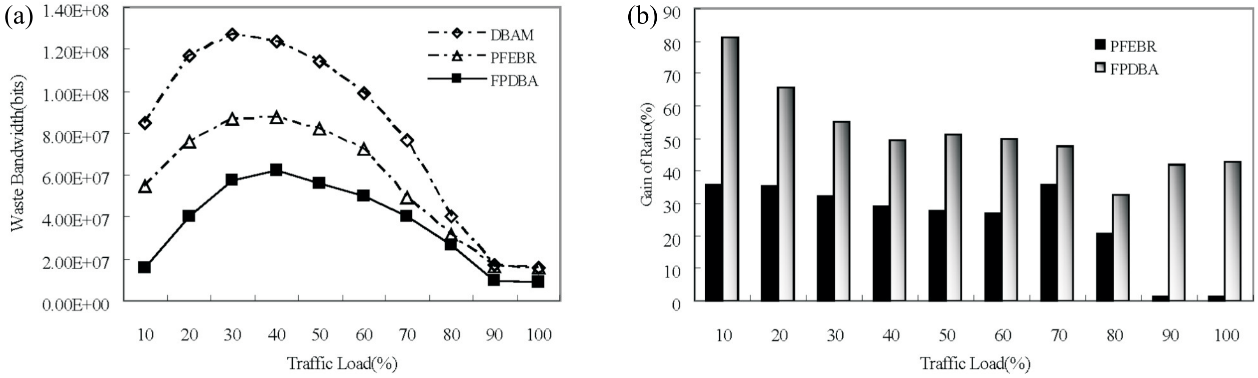

Figure 8. (a) Wasted bandwidth, (b) Gain ratio of bandwidth.

The gain ratio of bandwidth exceeds 30% when the traffic load is below 70%, which is shown in Figure 8(b). When the traffic load increases up to 70%, the FPDBA can still have 20–50% gain ratio of bandwidth more than the DBAM and 10–40% gain ratio of bandwidth more than the PFEBR. The reason is that the waiting time length is variable especially when some ONUs have large traffic variation, but the waiting time length of α in the DBAM is a fixed value which will cause prediction inaccuracy. The FPDBA also outperforms the PFEBR, the reason is that the estimation credit α in the PFEBR is assigned as $T^{W}_{i,n}$ / $T_{i,n}$, but the α is adjusted by FCE according to traffic variance dynamically in the FPDBA.

4.2 Throughput

Figure 9 compares the throughput vs. traffic load among the FPDBA, PFEBR, EAA and DBAM. The proposed FPDBA outperforms the PFEBR, EAA and DBAM when the traffic load exceeds 70%. The DBAM has the worst throughput because the inaccurate prediction problem and limit bandwidth allocation (LBA) are proven to have lower throughput under non-uniform traffic [5]. The EAA allocates more bandwidth to ONUs than requested [6], thus lowering system throughput.

4.3 End-to-End Delay

Figures 10 compare the average end-to-end packet delay among the FPDBA, PFEBR, EAA and DBAM of all EF, AF and BE traffic respectively. Figure 10(a) shows the proposed FPDBA outperforms the other three schemes when the traffic load is high. The DBAM has the worst performance because of serious prediction inaccuracy when the traffic has high variation. Additionally, the proposed FPDBA has less average end-to-end delay than the PFEBR because the FUDLC in the FPDBA obtains the optimal value of λ to predict accurately. In Figure 10(b), 10(c) and 10(d), the FPDBA can handle varying traffic of EF, AF and BE. The ITU-T recommendation G.114 specifies the delay for voice traffic in access network at 1.5 *ms* [13]. The end-to-end delay of EF traffic in four methodologies are below 1.5 *ms* when the traffic load under 80% and slight than 1.5 *ms* when the traffic load exceeds 90%, shown in Fig 10(b). However, the FPDBA has the least average end-to-end delay of EF traffic. Further-

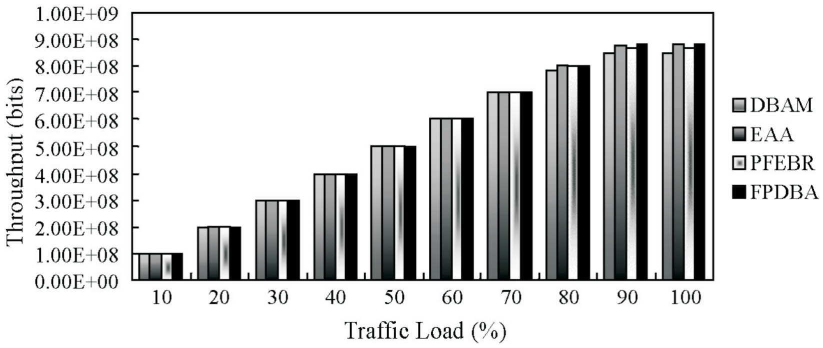

Figure 9. Throughput.

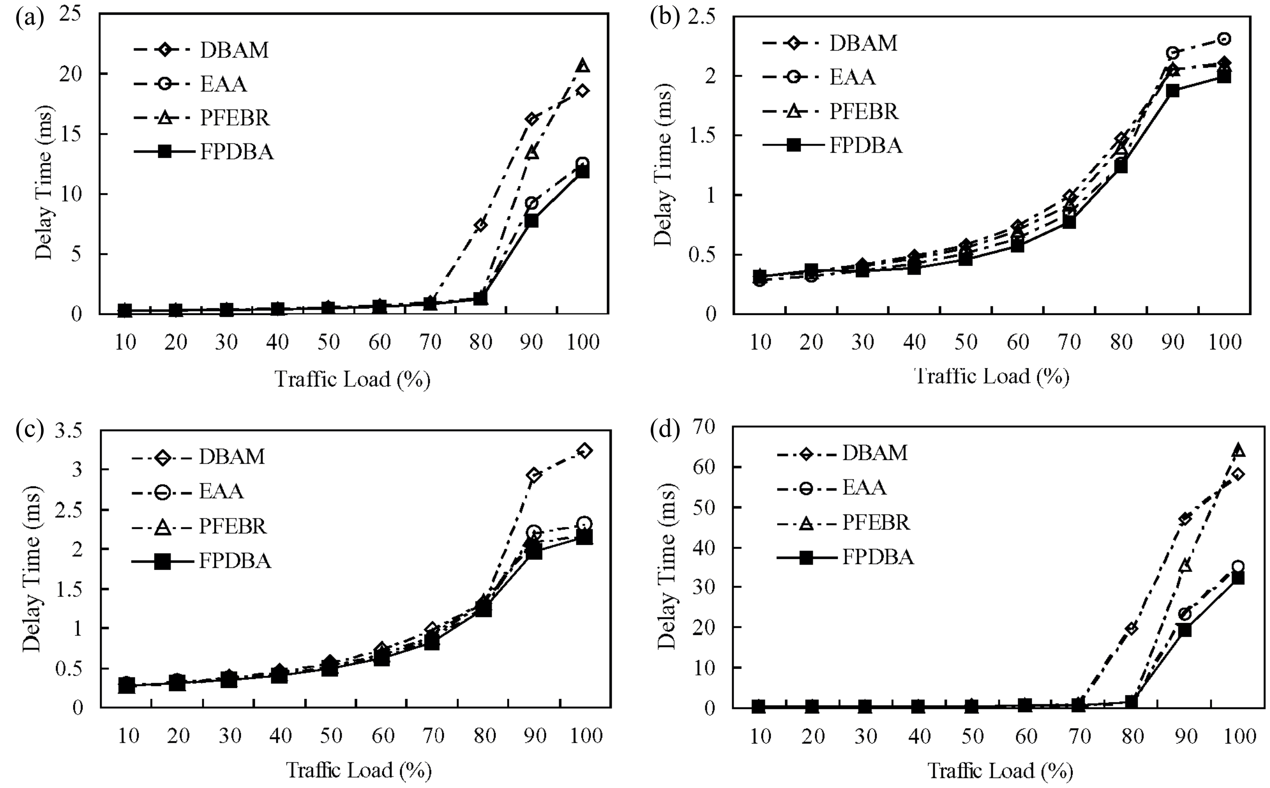

Figure 10. (a) Average end-to-end delay, (b) End-to-end delay for EF traffic, (c) End-to-end delay for AF traffic, (d) End-to-end delay for BE traffic

more, the EAA cannot redistribute the excessive bandwidth to ONUs fairly that results in longer end-to-end delay. The packet delay time has three components: polling delay, grant delay and queuing delay [12]. The EAA reduces the polling delay by shorter polling cycle, however, increases the flow of control messages which results in diminishing downlink data available bandwidth, shown in Figure 11. Prediction-based schemes, the FPDBA and PFEBR, will decrease more queuing delay than polling delay. Therefore, the FPDBA can reduce more packet delay and the traffic of control messages.

4.4 Downlink Data Available Bandwidth

Figure 11 compares the downlink data available bandwidth vs. traffic load among the FPDBA, PFEBR, EAA and DBAM. The proposed FPDBA has more downlink data available bandwidth than the EAA, and is close to those of the PFEBR and DBAM. The reason is that the FPDBA, PFEBR and DBAM have variable cycle time for data transmission than the fixed cycle time scheme of the EAA. Because of more GATE messages of the EAA, the downlink data available bandwidth less than the FPDBA, PFEBR and DBAM.

4.5 Average Queue Length

Figure 12 compares the average queue length vs. traffic load among the FPDBA, PFEBR, EAA and DBAM. The FPDBA outperforms the other three schemes. The DBAM without excessive bandwidth allocation scheme yields the longest average queue length when the traffic load exceeds 70%. Owing to the unfairness of redistribute excessive bandwidth problem, the EAA cannot reallocate excessive bandwidth sufficiently. Furthermore,

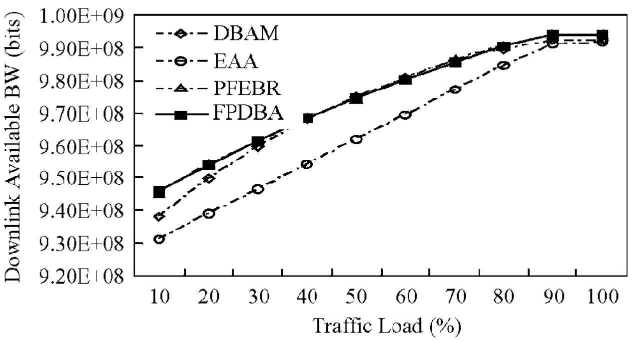

Figure 11. Downlink data available bandwidth.

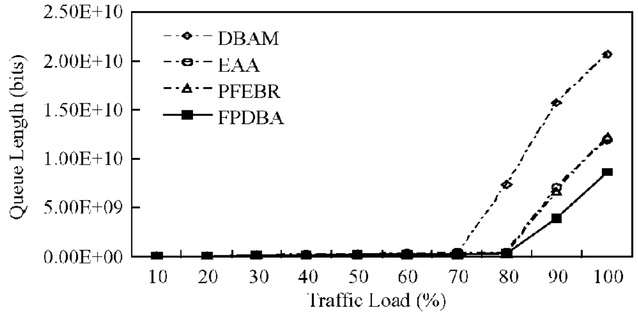

Figure 12. Average queue length.

the bandwidth allocate in the FPDBA is sufficient for transmitting the packet arrival during waiting time, thus reduce the queue length. The average queue length is accumulated dramatically when the offered load is more than 80%. The simulation result also shows that the FPDBA has less average queue length than the PFEBR after determines the optimal values of λ and α dynamically.

5. Conclusion

In this paper, the FPDBA algorithm based on the PFEBR is proposed to improve the prediction accuracy and enhance the system performance by obtaining optimal values of λ and α. Simulation results show that the FPDBA compares with the PFEBR and the DBAM in terms of wasted bandwidth, when the offered load increases up to 70%, the FPDBA can still have 20–50% gain ratio of bandwidth more than the DBAM and 10– 30% gain ratio of bandwidth more than the PFEBR. In the downlink data available bandwidth, the proposed FPDBA have 5×10^6 to 2×10^7 bits more than the EAA. The reason is that the FPDBA has variable cycle time for transmitting more data than that of fixed cycle time in the EAA, thus the FPDBA has less control messages than EAA during a period. As compared with the PFEBR, EAA and DBAM in terms of the packet end-to-end delay, the FPDBA can reduce average end-to-end packet delay from 2 *ms* to 8 *ms*. The FPDBA also reduce average queue length about 30% to 50% when the traffic load is high. In conclusion, the FPDBA outperforms PFEBR by obtaining optimal values of λ and α, and also outperforms DBAM and EAA.

References

[1] ITU-T Recommendations. Available: http://www.itu.int/ITUT/publications/recs.html.

[2] IEEE 802.3ah task force home page. Available: http://www.ieee802.org/3/efm.

[3] Hwang, I. S., Shyu, Z. D., Ke, L. Y. and Chang, C. C., “A Novel Early DBA Mechanism with Prediction-Based Fair Excessive Bandwidth Allocation Scheme in EPON,” *Computer Communications,* Vol. 31, pp. 1814–1823 (2008).

[4] Kramer, G., Mukherjee, B. and Pesavento, G., “IPACT: A Dynamic Protocol for an Ethernet PON (EPON),” *IEEE Communications Magazine,* Vol. 40, pp. 74–80 (2002).

[5] Son, K., Ryu, H., Chong, S. and Yoo, T., “Dynamic Bandwidth Allocation Schemes to Improve Utilization under Nonuniform Traffic in Ethernet Passive Optical Networks,” *IEEE International Conference on Communications,* Vol. 3, pp. 1766–1770 (2004).

[6] Zheng, J., “Efficient Bandwidth Allocation Algorithm for Ethernet Passive Optical Networks,” *IEE Proceedings Communications,* Vol. 153, pp. 464-468 (2006).

[7] Assi, C., Ye, Y., Dixit, S. and Ali, M. A., “Dynamic Bandwidth Allocation for Quality-of-Service over Ethernet PONs,” *IEEE Journal on Selected Areas in Communications,* Vol. 21, pp. 1467-1477 (2003).

[8] Luo, Y. and Ansari, N., “Bandwidth Allocation for Multiservice Access on EPONs,” *IEEE Communications Magazine,* Vol. 43, pp. S16–S21 (2005).

[9] Lee, C., “Fuzzy Logic Control Systems: Fuzzy Logic Controller, Part-II,” *IEEE Transactions on Systems, Man and Cybernetics,* Vol. 20, pp. 404–435 (1990).

[10] Chandramathi, S. and Shanmugavel, S., “A Novel Fuzzy Approach to Estimate Cell Loss Probability for Self-Similar Traffic in ATM Networks,” *IEEE sixth international conference on computers and communication* (*ISCC 2001*), Tunisia, pp. 260–265 (2001).

[11] Willinger, W., Taqqu, M. S. and Erramilli, A., “A Bibliographical Guide to Self-Similar Traffic and Performance Modeling for Modern High-Speed Networks,” *Stochastic Networks: Theory and Applications,* Royal Statistical Society Lecture Notes Series, Vol. 4, Oxford University Press (1996).

[12] Bai, X. and Shami, A., “Modeling Self-Similar Traffic for Network Simulation,” *Technical Report,* NetRep-2005-01, April (2005).

[13] ITU-T Recommendation G.114, “One Way Transmission Time,” May (2000).

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