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# The Performance Evaluation of Prediction-based Fair Wavelength Assignment and Bandwidth Allocation Scheme in WDM-EPON

I-Shyan Hwang[a], Zen-Der Shyu[b], Chun-Che Chang[a], Jhong-Yue Lee[a]
Department of Computer Engineering and Science, Yuan-Ze University, Chung-Li, Taiwan, 32026[a]
Department of General Studies, Army Academy, Chung-Li, Taiwan, 32092[b]

***Abstract-* This study proposes a prediction-based fair wavelength and bandwidth allocation (PFWBA) scheme to enhance the differentiated services for WDM-EPON. The proposed PFWBA scheme is based on the dynamic wavelength allocation (DWA) and prediction-based fair excessive bandwidth allocation (PFEBA) which is our previous work. The DWA can operate in coordination with an unstable degree list of PFEBA to allocate the available time slots of wavelength precisely. Simulation results show the evaluation of ONU buffer size for the proposed PFWBA scheme in terms of average packet delay, jitter performance and average packet loss ratio.**

*Keywords:* WDM-EPON, differentiated services, PFEBA.

## I. INTRODUCTION

Compared with the current access network technologies, the passive optical network (PON) is a promising solution for the full service access network, since optical fiber can satisfy the increasing bandwidth demand. Two standards organizations, International Telecommunications Union Standardization Sector (ITU-T) and Institute of Electrical and Electronics Engineers (IEEE), have led the discussion of PON specifications. The ITU-T recommends a series of ATM-based Broadband PON systems (i.e., ATM-PON, BPON and GPON). Furthermore, Ethernet PON (EPON) has been discussed in IEEE 802.3ah as an extension of Gigabit-Ethernet [1]. Although the EPON or ATM-based PON provides higher bandwidth than traditional copper-based access networks, the bandwidth of the PON needs to be increased further. The WDM-PON architecture can adopt wavelength-division multiple access (WDMA) to support multiple wavelengths in either or both upstream and downstream directions [2]. For employing the WDMA technology, the passive arrayed waveguide grating (AWG) is deployed in the WDM-PON architecture. The AWG allows for spatial reuse of the wavelength channels; thus, a multi-wavelength source at the OLT is used to transmit multiple wavelengths to the various optical network units (ONUs) [3]. However, the limitations of WDM-PON are lack of mature device technologies, lack of suitable network protocols to support the architecture, and high overall cost of deploying optical modules [4]. To integrate the advantages of EPON and WDM-PON to provide high link capacity, and to lower the overall system cost, a smooth migration to WDMA from EPON is expected a promising solution for optical access network technology.

The WDM-EPON is the expected solution which employs EPON and WDM-PON systems to provide additional link capacity and lower the cost of optical units. The WDM-EPON manages different wavelength channels in order to increase the available bandwidth of the EPON, but not to increase the cost of the system [5], [6]. In the WDM-EPON architecture, the optical line terminal (OLT) node is upgraded as an array of fixed-tuned transceivers, and reserves one control wavelength channel for the OLT to forward broadcast frames to each ONU. For the ONU node structure, the WDM-EPON adds tunable transceivers which employ different tuning times and tuning ranges. In the downstream direction, WDM-EPON broadcasts control messages from the OLT to each ONU through the entire bandwidth of one wavelength. Each ONU discards or accepts the incoming frames depending on the packet header addressing. In the upstream direction, WDM-EPON adopts time-division multiple access (TDMA) coupled with multi-point control protocol data unit (MPCPDU) mechanism to avoid collision. The MPCPDU involves both *GATE* and *REPORT* messages. The OLT allocates upstream bandwidth to each ONU by sending *GATE* messages which contains a timestamp, granted timeslots and wavelengths indicating the periods during which the ONU can transmit data. Each ONU can send *REPORT* messages concerning the queue state to the OLT, enabling the OLT to allocate the appropriate upstream bandwidth, wavelengths and timeslots to each ONU. With multiple ONUs sharing the same upstream bandwidth and wavelengths to transmit data on the WDM-EPON, any data collision lengthens the end-to-end delay and degrades the system performance. Hence, the bandwidth and wavelength allocation is a major concern of research in the WDM-EPON, especially with the large demand for bandwidth and critical applications [5], [6].

Wavelength and bandwidth allocation schemes can be divided into two categories, *Static Wavelength Dynamic Time* (SWDT) and *Dynamic Wavelength Dynamic Time* (DWDT) which is also called *Dynamic Wavelength and Bandwidth Allocation* (DWBA) [7]. In the SWDT, the OLT allocates wavelengths statically and timeslots dynamically. The ONUs are divided into different groups according to the number of wavelengths, and each group of ONUs shares a pre-defined wavelength. However, the number of ONUs on each wavelength is identified in the SWDT, which does not exploit the inter-channel statistical multiplexing, thus lowering utilization. The DWBA assigns the bandwidth and wavelength based on the requested bandwidth, wavelength loading and quality of service (QoS) requirement by each ONU [6], [7]. The DWBA can also exploit both inter-channel and intra-channel statistical multiplexing. Therefore, the DWBA scheme provides more efficient bandwidth allocation than the SWDT scheme, allowing each ONU to share the network resources, and improving QoS for end-users.

This study proposes a robust prediction-based fair wavelength and bandwidth allocation (PFWBA) scheme, which includes the *dynamic wavelength allocation* (DWA) [7] and *Early DBA* (E-DBA) *mechanism* [8]. The E-DBA mechanism for prediction-based fair excessive bandwidth allocation (PFEBA) scheme is our previous research. The E-DBA improves prediction accuracy by delaying some *REPORT* messages of unstable traffic ONUs, and assigns linear estimation credit to predict the arrival of traffic during waiting time. The DWA can operate in coordination with the unstable degree list to allocate the wavelength available time precisely. Furthermore, to improve the system performance, the PFWBA scheme also considers the fairness of excessive bandwidth reallocation among ONUs in the WDM-EPON for differentiated traffic classes.

The rest of this paper is organized as follows. Section 2 describes related work of DWBA in WDM-EPON. Section 3 presents the PFWBA scheme, which incorporates the DWA and the E-DBA mechanism for dealing with prediction and fairness allocation of wavelength and bandwidth. Next, Section 4 presents the simulation results of the proposed scheme. Conclusions are finally drawn in Section 5.

## II. RELATED WORK

The WDM-EPON can increase the number of wavelengths by employing wavelength-division multiple access (WDMA), so that multiple wavelengths may be supported in either or both upstream and downstream directions. In WDM-EPON, the OLT provides multiple wavelengths for upstream and downstream, which are shared by ONUs. Therefore, allocating the bandwidth and wavelength efficiently is the key factor to satisfying various QoS requirements for end-users. Recent studies on wavelength and bandwidth allocation in WDM-EPON can be classified as dynamic wavelength allocation (DWA) and dynamic bandwidth allocation (DBA). The WDM-EPON DWA concerns how the OLT allocates suitable wavelength from multiple wavelengths to ONUs. The WDM-EPON DBA is applied, after the OLT assigns wavelengths to ONUs, in order to allocate bandwidth for each ONU efficiently according to the QoS requirement and network traffic.

Previously proposed DWA systems include the sequential scheduling algorithm [9], which emulates a virtual global first-in-first-out queuing for all incoming requests, and assigns a suitable wavelength for each request. This scheduling algorithm may suffer from wasted bandwidth and poor fairness guarantee if some ONUs have large round trip times (RTTs). To overcome the wasted bandwidth problem, K.S. Kim *et al.* [10] presents a batch scheduling system that provides priority queuing by scheduling over more than one frame. The batch scheduling system stores the bandwidth requests arriving at OLT during the batch period in queues, and schedules them at the end of batch period. The scheduling delay of the batch scheduling system may increase when the system load is very low and the batch period is short [11]. M. McGarry *et al.* investigated another scheduling algorithm for *REPORT* messages such as *online scheduling* and *offline scheduling* [5]. In online scheduling, the OLT follows a grant-on-the-fly manner to allocation timeslots. The OLT allocates a transmission window for each ONU as soon as the OLT receives *REPORT* message from each ONU for the next cycle. Unlike the online scheduling, the OLT follows a wait-for-all manner in offline scheduling. The OLT allocates transmission windows for all ONUs in a round-robin manner after having received all *REPORT* messages from all ONUs for the next cycle. The offline scheduling with wait-for-all leads to a long waiting time and idle period because of the long inter-scheduling cycle gap.

In terms of WDM-EPON DBA, K.H. Kwong *et al.* [12] proposed the WDM IPACT-ST scheme based on the interleaved polling with adaptive cycle time (IPACT), which is proposed for EPON access network [1]. The WDM IPACT-ST applies IPACT to multi-channel PON, where ONUs are equipped with fixed transceivers. Nonetheless, the WDM IPACT-ST lacks the ability to handle the excessive bandwidth, which is collected from lightly-loaded ONUs. As an extension of the WDM IPACT-ST, the excessive bandwidth reallocation (EBR) [7], [13] redistributes the available excessive bandwidth to heavily-loaded ONUs according to the proportion of each request, and improves the performance in terms of packet delay. However, EBR has some drawbacks, namely unfairness and excessive bandwidth allocated to ONUs over that requested. This is termed the *redundant bandwidth problem* [12]. A.R. Dhaini *et al.* [7] proposed the DWBA3 scheme, the extension of the EBR in the WDM-EPON, which allocates the bandwidth for two steps. The DWBA3 allocates first the guaranteed bandwidth for heavily-loaded ONUs, and the requested bandwidth for lightly-loaded ONUs. Finally, upon receiving all *REPORT* messages, the DWBA3 redistributes the available excessive bandwidth to heavily-loaded ONUs based on the proportion of each request in next cycle. The upstream in different transmission cycle for heavily-loaded ONUs increases the number of guard time, which decreases the available bandwidth, and increases the end-to-end delay.

The PFEBA [8] executes the DBA scheme after the *REPORT* messages from unstable traffic ONUs are received at the end of ONU$_{N-1}$, instead of at the end of ONU$_N$ in the standard DBA scheme. The operation reduces the idle period in the standard DBA scheme, and obtains more fresh information of unstable traffic ONUs to enhance the accuracy of prediction in the following cycle. Additionally, the bandwidth is allocated to each ONU in the next cycle according to 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 scheme of the PFEBA alleviates traffic variance by shortening the waiting time before transmitting data for unstable traffic ONUs, and thus improves prediction accuracy.

## III. THE PROPOSED DYNAMIC WAVELENGTH AND BANDWIDTH ALLOCATION

This study proposes a robust prediction-based fair wavelength and bandwidth allocation (PFWBA) scheme, which includes the dynamic wavelength allocation (DWA) and E-DBA mechanism of the PFEBA scheme. The E-DBA mechanism allocates the bandwidth to each ONU according to the decreasing order of unstable degree list and improves the prediction accuracy. Additionally, the DWA mechanism selects the wavelength with the least available time for each ONU to reduce the average delay time. To reduce the prediction inaccuracy resulting from a long waiting time, the DWA divides all ONUs into three groups based on the unstable degree list. The DWA can cooperate with the PFWBA scheme to select a suitable wavelength, and reduce the delay time for each ONU.

### *A. PFEBA Scheme with Early DBA Mechanism*

#### *1) The Operation of Early DBA Mechanism*

The E-DBA mechanism arranges the sequence of transmitting *REPORT* messages to OLT by delaying some unstable traffic ONUs of $\beta_V$. The E-DBA mechanism consists of two operations. First, the OLT executes the DBA scheme after the *REPORT* messages from $\beta_V$ are received at the end of ONU$_{N-1}$, as illustrated in Fig. 1, instead of ONU$_N$ in the standard DBA scheme. The operation reduces the idle period in the standard DBA scheme, and obtains the recent queue information for unstable traffic ONUs to improve the prediction accuracy. Second, the bandwidth request for each ONU is allocated based on the traffic variation of all ONUs in decreasing order, and $\beta_V$ is updated by assigning some unstable traffic ONUs with higher variations. This operation alleviates variance by shortening the waiting time for unstable traffic ONUs to enhance the prediction accuracy.

#### *2) PFEBA Scheme*

- *Unstable degree list*

The PFEBA calculates the variance of each ONU from the historical traffic required, and sorts the variances in decreasing order to obtain the unstable degree list. The variance of ONU$_i$, $V_i$, can be expressed as follows:

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

, where $B_{i,n}^{Total}$ represents the sum of differentiated traffic classes of ONU$_i$ in the n*th* cycle, $\overline{B}_i$ is the mean of the $B_{i,n}^{Total}$, i.e. $\overline{B}_i = \frac{1}{N_H}\sum_{n=1}^{N_H} B_{i,n}^{Total}$, and $N_H$ represents the number of historical *REPORT* messages piggybacked. $\beta_V$ denotes a set of ONUs in unstable degree list with a high variance which is greater than the mean variance $\overline{V}$, where $\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i$. The bandwidth prediction of each ONU after obtaining the unstable degree list is described as follows. Unlike the mechanism that piggybacks all *REPORT* messages in the data timeslots, the E-DBA mechanism shifts the *REPORT* messages of $\beta_V$ between the (N−1)*th* and N*th* ONU. The PFEBA requires the recent queue information of unstable traffic ONUs to avoid prediction inaccuracy, which degrades the system performance.

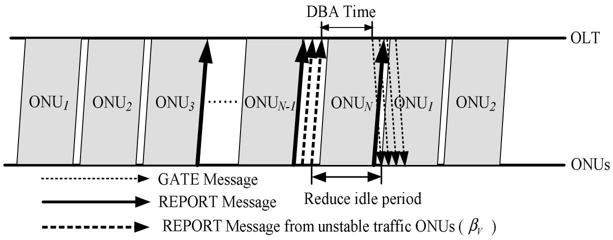


Figure 1. Operation with the proposed E-DBA mechanism

- *Prediction based on unstable degree list*

After the sequence of all ONUs from the unstable degree list is uploaded, the PFEBA predicts the traffic bandwidth required according to the unstable degree list. The predicted request, $R_{i,n+1}^{c}$, for differentiated traffic classes of all ONUs is defined as follows:

$$\begin{cases} R_{i,n}^{EF} = B_{i,n}^{EF} \\ R_{i,n+1}^{c} = (1+\alpha)B_{i,n}^{c}\ ,\ \ c \in \{AF,BE\} \end{cases} \qquad (2)$$

, where $B_{i,n}^{c}$ represents the requested bandwidth of ONU$_i$ in the n*th* cycle, for differentiated traffic classes $c \in \{AF, BE\}$, and $\alpha$ denotes the linear estimation credit modified from the PFEBA [8]. To achieve a better performance for a time-critical application, such as EF traffic, the constant bit rate (CBR) bandwidth should be assigned to the ONUs according to the rate of these applications. Therefore, this study assigns the CBR bandwidth to EF traffic.

- *Excessive bandwidth allocation*

The PFEBA executes the EBR to assign uplink bandwidth to each ONU after it has finished predicting the bandwidth needed for each ONU. The PFEBA scheme can provide fairness for excessive bandwidth allocation according to the guaranteed bandwidth rather than requested bandwidth [13], with no partiality or increase in bandwidth utilization. The operation of fair EBR in the PFEBA is described as follows. First, calculate the $R_{i,n}^{Total}$ of all ONUs. The available bandwidth, $B_{available}$, can be expressed as

$$B_{available} = C_{capacity} \times (T_{cycle} - N \cdot g - N_v \cdot g) - N \times 512 \qquad (3)$$

, where $C_{capacity}$ represents the OLT link capacity (bits/sec), $T_{cycle}$ denotes the maximum cycle time; $g$ is the guard time; $N$ is the number of ONUs, and $N_V$ is the number of ONUs in $\beta_V$. The ONU$_i$ with the maximal residue bandwidth, i.e. $\max(S_i - R_{i,n}^{Total})$, is then selected from unassigned ONUs. The granted bandwidth for ONU$_i$, $G_{i,n+1}^{Total}$, is given as follows:

$$G_{i,n+1}^{Total} = \min\left( B_{available} \times \frac{S_i}{\sum_{k \in unassigned} S_k}\ ,\ R_{i,n}^{Total} \right) \qquad (4)$$

, where $R_{i,n}^{Total}$ represents the sum of the differentiated traffic load after being predicted from ONU$_i$ in the n*th* cycle; $S_i \cdot (\sum_{k \in unassigned} S_k)^{-1}$ is the proportion of available bandwidth, $B_{available}$, granted to ONU*i*. The granted bandwidth for EF, AF and BE classes are described as follows:

$$\begin{cases} G_{i,n+1}^{EF} = R_{i,n}^{EF} \\ G_{i,n+1}^{AF} = \min\left(G_{i,n+1}^{Total} - G_{i,n+1}^{EF}, R_{i,n}^{AF}\right). \\ G_{i,n+1}^{BE} = G_{i,n+1}^{Total} - G_{i,n+1}^{EF} - G_{i,n+1}^{AF} \end{cases} \qquad (5)$$

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

### B. Dynamic Wavelength Allocation

The PFWBA defines the following global status variables used in the scheme description:

*1) CAT: Channel available times. CAT[i] = t indicates that the wavelength $\lambda_i$ is available for transmission after time t, where i = 1, 2, ..., w, and w is the number of wavelengths.*

*2) RTT: RTT[i] represents the round trip time (RTTs) between the OLT and the ith ONU.*

The PFWBA considers the unstable degree list when scheduling the upload sequence after collecting all *REPORT* messages from the ONUs in order to improve the prediction accuracy. First, the PFWBA divides all ONUs into three levels based on the variance of all ONUs and allocates the wavelength for each ONU group by group, which is determined as follows:

$$\begin{cases} Group\ 1, & if\ \text{ONU}_i \in \beta_V \\ Group\ 2, & V_i > \overline{V}\ and\ \text{ONU}_i \notin \beta_V\ . \\ Group\ 3, & otherwise \end{cases}$$

The wavelength scheduling process is described as follows:

1) *Schedule the PFWBA from Group1 to Group3 according to the unstable degree list.*
2) *Select the requested frame in the same Group with the minimum transmission time, and schedule its transmission.*
3) $Transmission\quad time = RTT[i] + g + transmission\ timeslots$, where $g$ is the guard time, and the transmission timeslots are obtained from the PFEBA.
4) *Choose the earliest available wavelength transmission time CAT[i].*
5) *Update the CAT[i] is as CAT[i] = transmission time + CAT[i].*
6) *Repeat the above operation until the requested frames in the same Group are scheduled, and schedule the requested frames in the following Group.*

TABLE I
SIMULATION SCENARIO

| | |
|---|---|
| Number of ONUs | 32 or 64 |
| Number of wavelength | 1 or 2 |
| Upstream/downstream link capacity | 1 Gbps |
| OLT - ONU distance (uniform) | 10-20 *km* |
| Maximum cycle time | 2 *m*s |
| Guard time | 5 $\mu s$ |
| Control message length | 0.512 $\mu$s |

## IV. PERFORMANCE ANALYSIS

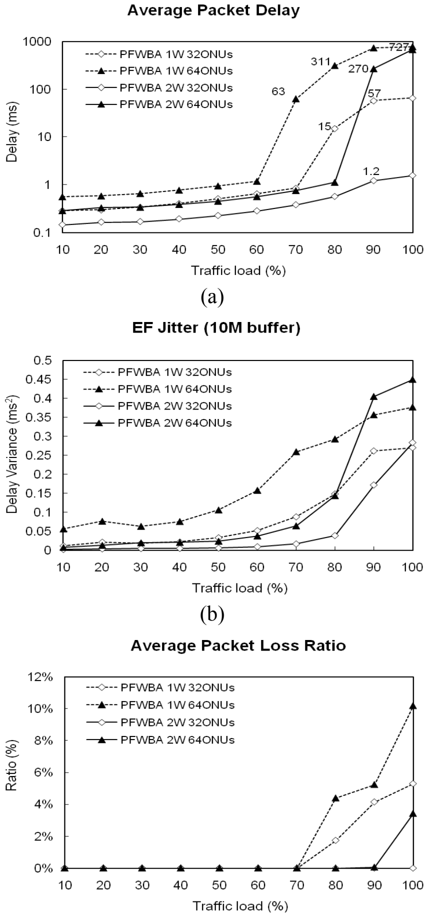
The performance evaluation of ONU buffer size for the proposed PFWBA scheme was compared in terms of average packet delay, jitter performance and average packet loss ratio. The results were examined by the OPNET simulation tool in different buffer situation. The duration time of simulation in OPNET is designed as 30 seconds. Table 1 summarizes the simulation scenario. The service policy was first-in first-out. For the traffic model considered here, an extensive study shows that most network traffic can be characterized according to self-similarity and long-range dependence (LRD) [14]. This model was adopted to generate highly bursty BE and AF traffic classes with the Hurst parameter of 0.7. The packet sizes were uniformly distributed between 64 and 1518 bytes. Additionally, high-priority traffic was modeled by a Poisson distribution, and the packet size was fixed to 70 bytes [15]. The traffic profile was as follows: 20% of the total generated traffic was considered as high priority, and the remaining 80% was equally distributed between low- and medium-priority traffic [16].

### 1) 10M buffer situation

Figure 2 compares the average packet delay, EF jitter performance and average packet loss ratio of the PFWBA with different numbers of wavelengths and ONUs vs. traffic loads in the 10M buffer situation. Simulation results show that lowering the number of wavelengths and increasing the number of ONUs lengthen the average packet delay, as shown in Fig. 2(a). Figure 2(b) compares the jitter performance of the PFWBA for EF traffic with different numbers of wavelengths and ONUs vs. traffic loads, respectively. The delay variance $\sigma^2$ is calculated as $\sigma^2 = \frac{\sum_{i=1}^{N}(d_i^{EF} - \overline{d})^2}{N}$, where the $d_i^{EF}$ represents the EF delay time of packet $i$, and $N$ is the total number of received EF packets. Simulation result shows the PFWBA with two wavelengths and 64 ONUs with the highest delay variance when the traffic load exceeded 90%. The reason is that the number of ONUs with higher variance is increased when the traffic load exceeds 90% which causes the prediction model suffer serious inaccuracy and deteriorates system performance. The average packet loss ratio is shown in Fig. 2(c) with a 10M buffer limit.

### 2) Infinite buffer situation

Figure 3 compares the average packet delay and jitter performance of the PFWBA with different numbers of wavelengths and ONUs vs. traffic loads in infinite buffer situation. Simulation results show that the average packet

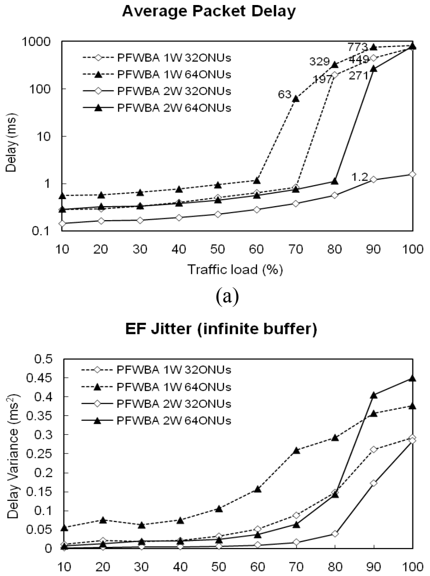


(a)

(b)

(c)

Figure 2. 10M buffer situation (a) Packet Delay (b) Jitter Performance (c) Packet Loss Ratio



(a)

(b)

Figure 3. Infinite buffer situation (a) Packet Delay (b) Jitter Performance

delay is slight higher than 10M buffer situation, as shown in Fig. 3(a). The result shows that the 10M buffer is enough for each ONU which has the similar results shown in [6]. The EF delay variance, shown in Fig. 3(b), is the same as the 10M buffer situation. The reason is that the PFWBA allows the high-priority traffic to be transmitted first. Therefore, the buffer situation will not affect the EF jitter performance.

## V. CONCLUSIONS

The proposed PFWBA scheme integrates an efficient dynamic wavelength allocation and E-DBA mechanism of the PFEBA to improve the prediction accuracy and system performance. Simulation results show that the PFWBA can reduce the overall end-to-end delay in differentiated traffic.

## REFERENCES

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

[2] N.J. Frigo, P.P. Iannone, P.D. Magill, T.E. Darcie, M.M. Downs, B.N. Desai, U. Koren, T.L. Koch, C. Dragone, H.M. Presby, and G.E. Bodeep, “Wavelength-division multiplexed passive optical network with cost-shared components”, *IEEE Photonics Technology Letters*, vol. 6, no. 11, pp. 1365-1367, Nov. 1994.

[3] S.J. Park, C.H. Lee, K.T. Jeong, H.J. Park, J.G. Ahn, and K.H. Song, “Fiber-to-the-home services based on wavelength division multiplexing passive optical network”, *Journal of Lightwave Technology*, vol. 22, no. 11, pp. 2582-2591, Nov. 2004.

[4] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, “Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]”, *Journal of Optical Networking*, vol. 4, no. 11, pp. 737-758, Nov. 2005.

[5] M. McGarry, M. Maier, and M. Reisslein, “WDM Ethernet passive optical networks”, *IEEE Communications Magazine*, vol. 44, no. 2, pp. 15-22, Feb. 2006.

[6] M. McGarry, M. Maier, and M. Reisslein, “An evolutionary WDM upgrade for EPONs”, Technical Report (Arizona State University), 2005.

[7] A.R. Dhaini, C.M. Assi, M. Maier, and A. Shami, “Dynamic Wavelength and Bandwidth Allocation in Hybrid TDM/WDM-EPON Networks”, *Journal of Lightwave Technology*, vol. 25, no. 1, pp. 277-286, Jan. 2007.

[8] I.S. Hwang, Z.D. Shyu, L.Y. Ke, and C.C. Chang, “A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON”, *Computer Communications*, vol. 31, no. 9, pp. 1814-1823, Jun. 2008.

[9] F.T. An, K.S. Kim, D. Gutierrez, S. Yam, E. (S.T.) Hu, K. Shrikhande, and L.G. Kazovsky, “SUCCESS: A next-generation hybrid WDM/TDM optical access network architecture”, *Journal of Lightwave Technology*, vol. 22, no. 11, pp. 2557-2569, Nov. 2004.

[10] K.S. Kim, D. Gutierrez, F.T. An, and L.G. Kazovsky, “Batch scheduling algorithm for SUCCESS WDM-PON”, *GLOBECOM - IEEE Global Telecommunications Conference*, vol. 3, pp. 1835-1839, 2004.

[11] K.S. Kim, D. Gutierrez, F.T. An, and L.G. Kazovsky, “Design and performance analysis of scheduling algorithms for WDM-PON under SUCCESS-HPON architecture”, *Journal of Lightwave Technology*, vol.23, no. 11, pp. 3716-3731, Nov. 2005.

[12] K.H. Kwong, D. Harle, and I. Andonovic, “Dynamic bandwidth allocation algorithm for differentiated services over WDM-EPONS”, 9th *IEEE Singapore International Conference on Communication Systems*, pp. 116-120, 2004.

[13] J. Zheng, “Efficient bandwidth allocation algorithm for Ethernet passive optical networks”, *IEE Proceedings Communications*, vol. 153, no. 3, pp. 464-468, June 2006.

[14] W. Willinger, M.S. Taqqu, and A. Erramilli, “A bibliographical guide to self-similar traffic and performance modeling for modern high-speed networks”, in Stochastic Networks, 1996. F. P. Kelly, S. Zachary and I. Ziedins (eds.), Oxford University Press, Oxford, pp. 339-366, 1996.

[15] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, “An Architecture for Differentiated Services”, IETF RFC 2475, Dec. 1998.

[16] X. Bai and A. Shami, “Modeling Self-Similar Traffic for Network Simulation”, Technical report, NetRep-2005-01, April 2005.