A Novel Dynamic Wavelength and Bandwidth Allocation Scheme for WDM-EPON with Survivable Network Architectures

I-Shyan Hwang, Zen-Der Shyu, Chun-Che Chang

***Abstract*—In this article, we discuss the dynamic wavelength and bandwidth allocation scheme for survivable network architectures and propose a novel fault-tolerant architecture in WDM-EPON, *Cost-based Fault-tolerant WDM-EPON* (*CFT-WDM-EPON*), which only equips a backup fiber to provide overall protection for optical components. Furthermore, a *Prediction-based Fair Wavelength and Bandwidth Allocation* (*PFWBA*) scheme is also proposed to enhance the differentiated services for WDM-EPON based on Dynamic Wavelength Allocation (DWA) and *Prediction-based Fair Excessive Bandwidth Allocation* (*PFEBA*) which is our previous work. The PFEBA involves an *Early-DBA* mechanism, which 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 proposed dynamic wavelength allocation scheme can operate in coordination with the unstable degree list to allocate the available time of wavelength precisely. Simulation results demonstrate that the proposed wavelength and bandwidth allocation scheme (PFWBA) is able to provide excellent performance in terms of average delay and delay-variation as compared with other well-known methodologies.**

***Index Terms*—PON, Fault tolerance, WDM, Wavelength and bandwidth allocation, PFEBA.**

I. Introduction

With the ever-increasing number of users that use high bandwidth for broadband multimedia traffic over the Internet, such as interactive games, videoconference, high-definition television (HDTV) and other high-speed services, high growth of access network is the most glaring issue in the communication industry. Compared with the current access network technologies, passive optical network (PON) technologies are a promising solution for the full service access network, since optical fiber can satisfy the increasing bandwidth demand. A PON is a point-to-multipoint optical network with no active elements in the transmission path from the source to destinations. Typically, it consists of a centralized optical line terminal (OLT), splitter, and multiple associated optical network units (ONUs) to deliver broadband packet and reduce the cost relative to maintenance and power. The OLT resides in a center office (CO) that connects the optical access network to the wide area network (WAN) or metropolitan area network (MAN).

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. 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 has gained increasing attention from industry due to the convergence of low-cost Ethernet equipment and fiber infrastructure. Even though the EPON or ATM-based PON utilizes the bandwidth of fiber effectively, it has limitations in the increase of transmission speed. On the other hand, the wavelength-division multiple-access (WDMA) scheme, WDM-PON, becomes more favorable as the required bandwidth increases.

The WDM-PON architecture [1], illustrated in Fig. 1, can adopt WDMA to support multiple wavelengths in either or both upstream and downstream directions. For employing the WDMA technology, the passive arrayed waveguide grating (AWG) is deployed in the WDM-PON architecture. The AWG is a passive optical device which is employed for (de)multiplexing a large number of wavelengths. Additionally, 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 ONUs [2]. In the WDM-PON, such a framework provides several benefits, such as guaranteed Quality-of-Service (QoS), high security and privacy. However, the limitations of WDM-PON are lack of mature device technologies, lack of suitable network protocols and software to support the

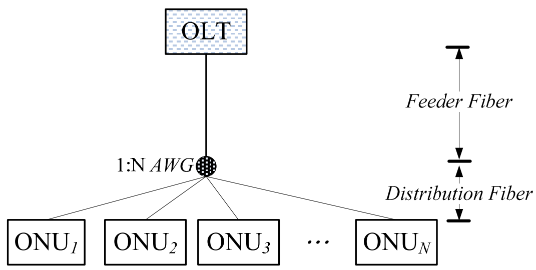

Fig. 1 The tree-based WDM-PON Architecture

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architecture, and high overall cost of deploying optical modules [3-5]. 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 next-generation 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. WDM-EPON manages different wavelength channels in order to increase the available bandwidth of the EPON, but not to impose any particular WDM architecture, which would increase the cost of the system [6, 7]. In the WDM-EPON architecture, the 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 all ONUs. For the ONU node structure, the WDM-EPON adds tunable transceivers which employ different tuning times and tuning ranges. The WDM-EPON provides bi-directional transmissions, namely downstream transmission from OLT to ONUs, and upstream transmission from ONUs to OLT. In the downstream direction, WDM-EPON broadcasts control messages from the OLT to each ONU through the entire bandwidth of one wavelength. Each ONU accepts or discards the incoming frames depending on the packet header addressing. In the upstream direction, 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 MPCPDU messages in 64-byte MAC control frames. Each GATE MPCPDU message 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.

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 referred as *Dynamic Wavelength and Bandwidth Allocation* (*DWBA*) [8]. 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 system utilization. The DWBA assigns the bandwidth and wavelength based on the requested bandwidth, wavelength loading and QoS requirement by each ONU [7, 8]. 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.

Another significant issue in the WDM-EPON is how to protect and recover the optical failure in the WDM-EPON system. Since optical passive networks transmit aggregated high-speed data from several hundreds of end-users, failure in network units or links results in serious problems. The researches in fault tolerance of WDM-based PON topology have recommended duplicate optical fiber and protection switching in the recent years [9-14]. However, these schemes are insufficient due to its high redundancy, which leads to a high cost. This article proposes a novel fault-tolerant architecture for WDM-EPON, *Cost-based Fault-tolerant WDM-EPON* (*CFT-WDM-EPON*), to lower the cost of conventional protection architecture, and in the short term to recover the functionality of the failed equipment. The CFT-WDM-EPON can recover the optical failure by fast wavelength switching between control and data channel, and only equips the backup feeder fiber to connect the adjacent PON system in order to economize the cost of deployment. This system not only protects the optical nodes such as the OLT, but also protects optical fibers such as feeder fibers. Additionally, this article also proposes a robust prediction-based fair wavelength and bandwidth allocation (PFWBA) scheme, which includes the *Dynamic Wavelength Allocation* (*DWA*) [8] and *Early DBA* (*E-DBA*) mechanism [15]. The E-DBA mechanism for prediction-based fair excessive bandwidth allocation (PFEBA) scheme is our previous research. The E-DBA reduces the idle period and waiting time in the conventional DBA scheme, and obtains fresh queue information for unstable traffic ONUs to improve the accuracy of prediction in the following cycle. 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 article is organized as follows. Section 2 describes related work of DWBA and existing protection scheme in WDM-EPON. Section 3 then proposes a novel fault-tolerant architecture, CFT-WDM-EPON, capable of providing overall protection for optical nodes and fibers. Next, Section 4 presents the PFWBA scheme, which incorporates the DWA and the E-DBA mechanism for dealing with prediction and fairness allocation of wavelength and bandwidth. The simulation results on the proposed system with other well-known methodologies are presented in Section 5 and conclusions are finally drawn in Section 6.

II. RELATED WORK

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 Quality-of-Service (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 (FIFO) 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, which decreases the total system throughput, 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 low and the batch period is short, degrading the overall performance [11]. M. McGarry *et al*. investigated another scheduling algorithm for REPORT messages such as *online scheduling* and *offline scheduling* [6]. 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 grant-on-the-fly manner of 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 (ISCG). However, neither online nor offline scheduling can provide fair and efficient intra-ONU bandwidth allocation and consider the QoS requirement and excessive bandwidth.

In terms of WDM-EPON DBA, K.H. Kwong *et al*. [16] proposed the WDM IPACT-ST scheme based on the interleaved polling with adaptive cycle time (IPACT), which was proposed for EPON access network [17]. 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) [8, 18] 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* [16].

A.R. Dhaini *et al*. [8] 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 [15] 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.

The fault tolerance of WDM-based PON topology has been discussed recently [9-14, 19]. The fault-tolerant architecture considers two types of network failure, namely link failure and node failure. The node protection of PON concentrates on the most important optical unit, namely OLT, and the link protection focuses on the feeder fibers that connect the OLT node with the remote node (RN) in the PON system. The protection mechanism for the PON topology constructs the backup links or nodes to recover the failure. In this pre-designed protection scheme, the protected links (nodes) are named working links (nodes) and the backup links (nodes) are named protection link (nodes) [20].

The authors of [9, 14] provide recovery mechanism against fiber-cut of feeder fiber which connects RN and OLT. H. Nakamura *et al*. [14] presented the protection fiber for feeder fibers to avoid the fiber-cut situation. The protection fiber may recover fiber failure occurring on the working fiber, but cannot recover from failure occurring on OLT. F.T. An *et al*. [9] proposed a new Hybrid TDM/WDM-PON architecture named Stanford University aCCESS Hybrid WDM/TDM Passive Optical Network (SUCCESS-HPON). The SUCCESS-HPON is based on a ring-plus-distribution-trees topology, which can provide users with better protection and restoration capabilities than conventional PONs. The SUCCESS provides bi-directional transmission on the same wavelength and fiber. Transmission occurs in reverse direction to recover the failure if the feeder fiber fails. However, the SUCCESS-HPON cannot provide protection for OLT and ONUs. Furthermore, the ring-plus-distribution-trees topology has a long round trip time (RTT) due to the very large number of ONUs. The authors of [12, 13] proposed redundant fibers topology to avoid the failure occurs. However, the protection for feeder and distribution fiber is provided by duplicate deployment of fiber in [12], which is not a cost-effective protection scheme. Furthermore, this protection architecture does not provide any recovery system for node failure. X. F. Sun *et al*. presented a ring-plus-tree architecture, which not only constructs protection links for feeder fibers, but also constructs protection links between ONUs [13]. The ONU still can transmit data by protection fiber connecting neighboring ONUs when the fiber-cut occurs on the distribution fibers. However, the protection architecture still cannot prevent node failure on optical nodes, and is not cost-effective due to duplicating deployment of fibers.

The above models focus on the fiber-cut situation on optical fibers, but do not consider optical node failures, even if the node failure may damage the PON system. If optical node failure occurs on the OLT, then the dynamic wavelength and bandwidth allocation cannot be processed. Additionally, the bandwidth and wavelength requested by all ONUs cannot be granted without leading to significant damage. Therefore, a good fault-tolerant scheme should protect the most important optical nodes, the OLT and the feeder fiber, to prevent the failures that degrade the system performance.

III. The Proposed CFT-WDM-EPON Architecture

The proposed protection architecture, CFT-WDM-EPON, based on WDM-EPON, comprises a centralized optical line terminal (OLT) and passive arrayed waveguide grating (AWG), and connects a group of associated optical network units (ONUs) to provide complete protection for overall PON architecture, illustrated in Fig. 2. Each PON system connects adjacent PON systems by protection feeder fiber, and each AWG connects two OLTs with many ONUs.

A. Normal situation

When no failures occur on the CFT-WDM-EPON, ONUs transmit the REPORT message to OLTs through wavelength, λ_{REPORT}, which is reserved for transmitting control messages for each ONU. The OLT identifies the ONU according to its unique MAC address. The OLT considers takes the loading balancing between different wavelengths when the OLT assigns wavelengths and bandwidth to each ONU by GATE MPCPDU message. The ONUs transmit data by different wavelengths, λ_α and λ_β, which are are routed and transmitted through different feeder fibers by AWG.

B. Fault Situation

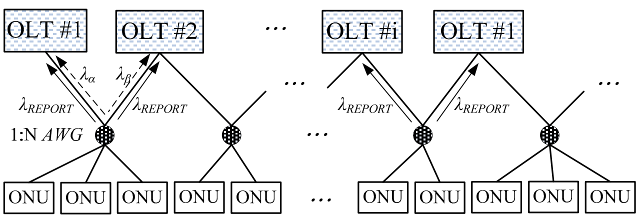


Fig. 2 The CFT-WDM-EPON architecture

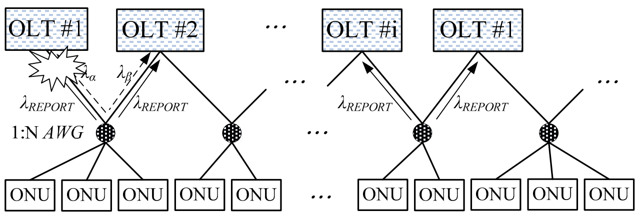


Fig. 3 The recovery scheme of the CFT-WDM-EPON

Table 1. Comparisons of the Protection Architecture

Architecture	Protected		#	#	# Feeder
	OL	Feeder Fiber	PON	OLT	Fiber
CFT-WDM-EPON	**Yes**	**Yes**	***N***	***N***	***2N***
F.T. An *et al.* [9]	**No**	**Yes**	***N***	***1***	***N+1***
H. Nakamura *et al.* [14]	**No**	**Yes**	***N***	***1***	***2N***
E.S. Son e*t al.*[12]	**No**	**Yes**	***N***	***N***	***2N***
X.F. Sun *et al.* [13]	**No**	**Yes**	***N***	***N***	***2N***

When the failure occurs on the CFT-WDM-EPON, OLT #1 cannot receive the REPORT messages from the ONUs in PON #1, and OLT #2 will starts the recovery scheme to take over the REPORT message from PON #1, and allocate wavelengths, λ_{REPORT} and λ_β, for upstream through protection feeder fiber to PON #1, as shown in Fig. 3.

The protection architectures in papers [9, 12-14] do not provide any recovery scheme for the OLT node, shown in Table 1. To prevent optical node failure and fiber failure from causing significant damage to the PON system, the CFT-WDM-EPON only equips backup optical fiber to provide the overall protection scheme. If no failures occur in the PON system, then the proposed architecture can share the loading of the working feeder fibers. The backup fibers recover the failed fibers when failures occur on the OLT or feeder fibers. The bandwidth and wavelength requests by the REPORT messages can still be transmitted through the backup fibers.

IV. The Proposed Dynamic Wavelength and Bandwidth Allocation

This article proposes a robust prediction-based fair wavelength and bandwidth allocation (PFWBA) scheme, which includes the dynamic wavelength allocation and *Early DBA* (E-DBA) mechanism of the prediction-based fair excessive bandwidth allocation (PFEBA) scheme. The E-DBA mechanism illustrated in Fig. 4(b), allocates the bandwidth to each ONU according to the decreasing order of unstable degree list. This is because obtaining more information when waiting for unstable traffic ONUs improves the prediction accuracy. The proposed E-DBA mechanism can improve the packet delay time by early execution the DBA scheme to reduce the idle period. Additionally, the dynamic wavelength allocation mechanism first 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 dynamic wavelength allocation divides all ONUs into three groups based on the unstable degree list. The dynamic wavelength allocation can cooperate with the PFWBA scheme to select a suitable wavelength, and reduce the delay time for each ONU. In this article, we discuss an WDM-EPON architecture that supports differentiated services and classify services into three priorities as defined in IETF RFC 2475 [21], namely the best effort (BE), the assured forwarding (AF), and expedited forwarding (EF). While EF services require bounded end-to-end delay and jitter specifications, AF is intended for services that are not

Table 2. Terminology

N_H	Number of historical REPORT messages recorded
V_i	The traffic variance of ONU$_i$
$\overline{V}$	The traffic mean variance of ONUs
β_V	The set of ONUs with higher traffic variance in unstable degree list
N_V	Number of ONUs in the β_V
T_{cycle}	Maximum cycle time in one 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
$G^c_{i,n+1}$	Granted upload BW of ONU$_i$ in the (n+1)*th* cycle, where $c \in \{EF, AF, BE\}$
w	Number of wavelengths
$CAT[i]$	Channel available time, where i = 1, 2, ...w
$RTT[i]$	Round trip times (RTTs) between the OLT and the *i*th ONU
λ_i	The *i th* wavelength, where i = 1, 2, …w

delay-sensitive but require bandwidth guarantees. Finally, BE applications are not delay-sensitive and do not require any jitter specifications. Terminology is summarized in Table 2.

A. PFEBA Scheme with Early DBA Mechanism

1) **Early DBA Mechanism**

The standard DBA scheme, illustrated in Fig. 4(a), piggybacks REPORT messages in data timeslots of ONUs, and starts the bandwidth allocation sequence after all REPORT messages are collected by the OLT. The E-DBA mechanism arranges the sequence of transmitting REPORT messages to OLT by delaying unstable traffic ONUs of β_V, which is represented as a set of ONUs with higher variance, and each variance is higher than the mean variance. The E-DBA mechanism consists of two operations. First, the OLT executes the DBA scheme after the REPORT messages from β_V are received at the end of ONU$_{N-1}$, as illustrated in Fig. 4(b), instead of ONU$_N$ in the standard DBA scheme, illustrated in Fig. 4(a). The operation reduces the idle period in the standard DBA scheme, and obtains the fresh queue information for unstable traffic ONUs to improve the prediction accuracy in the next cycle. Second, the bandwidth for each ONU in the next cycle is allocated based on the traffic variation of all ONUs in decreasing order, and β_V is updated by assigning some unstable traffic ONUs with higher variations. This operation alleviates variance by shortening the waiting time before transmitting data 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 of it, and sorts the variances in decreasing order to obtain the unstable degree list. The

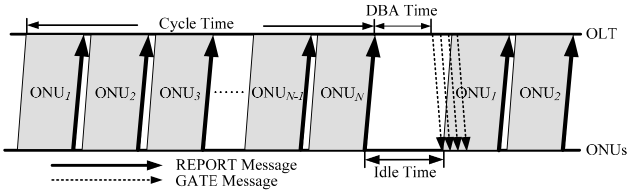


Fig. 4(a) Operation of standard DBA scheme

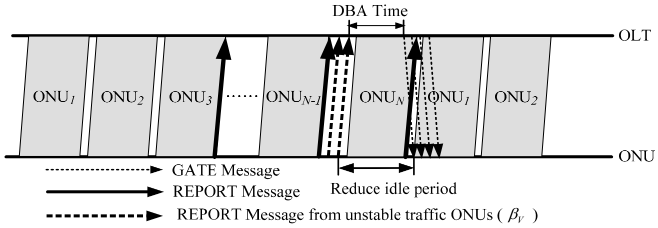


Fig. 4(b) Operation with the proposed Early DBA mechanism

variance of ONU*i*, V_i, can be expressed as follows:

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

, where $B^{Total}_{i,n}$ represents the sum of differentiated traffic classes of ONU*i* in the nth cycle, i.e. $B^{Total}_{i,n} = B^{EF}_{i,n} + B^{AF}_{i,n} + B^{BE}_{i,n}$, $\overline{B}_i$ is the mean of the $B^{Total}_{i,n}$, i.e. $\overline{B}_i = \frac{1}{N_H}\sum_{n=1}^{N_H} B^{Total}_{i,n}$, and N_H represents the number of historical REPORT messages piggybacked.

β_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 β_V between the (N−1)*th* and N*th* ONU, as illustrated in Fig. 4(b). The PFEBA requires the fresh queue information of unstable traffic ONUs to avoid prediction inaccuracy, which degrades the system performance.

- *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, $R^c_{i,n+1}$, for differentiated traffic classes of all ONUs is defined as follows:

$$\begin{cases} R^{EF}_{i,n} = B^{EF}_{i,n} \\ R^c_{i,n+1} = (1+\alpha)B^c_{i,n}, \quad c \in \{AF, BE\} \end{cases} \quad (2)$$

, where $B^c_{i,n}$ represents the requested bandwidth of ONU*i* in the nth cycle, for differentiated traffic classes $c \in \{AF, BE\}$, and α denotes the linear estimation credit modified from the PFEBA [15]. 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 article assigns the CBR bandwidth to EF traffic.

- *Excessive bandwidth allocation*

After having predicted the bandwidth needed for each ONU, the PFEBA then executes the excessive bandwidth reallocation (EBR) to assign uplink bandwidth to each ONU as illustrated in Fig. 5. The proposed PFEBA scheme can provide fairness for EBR based on the guaranteed bandwidth rather than requested bandwidth [18, 22], with no partiality and increase in bandwidth utilization. The operation of fair EBR in the proposed PFEBA is described as follows.

First, calculate the $R_{i,n}^{Total}$ of all ONUs. The available bandwidth, $B_{available}$, can be expressed as

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

, 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 β_V with control message length 512 bits (64 bytes).

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*, $G_{i,n+1}^{Total}$, in the next cycle is given as follows:

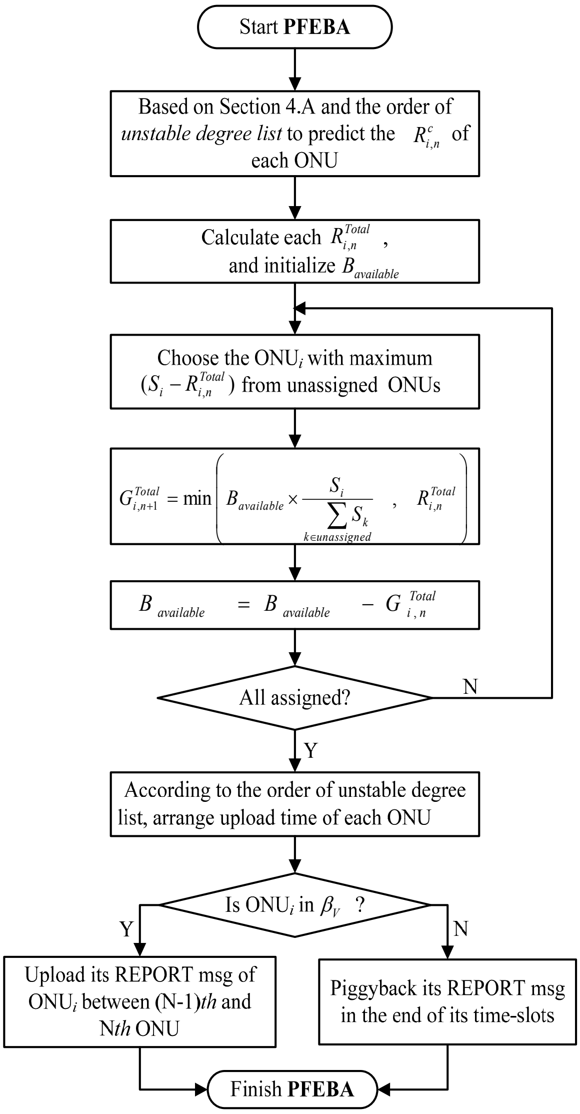


Fig. 5 The flowchart of PFRBA

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

, where $R_{i,n}^{Total}$ represents the sum of the differentiated traffic load after being predicted from ONU*i* in the nth cycle; $\frac{S_i}{\sum_{k \in unassigned} S_k}$ 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:

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

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

B. Dynamic Wavelength Allocation

This section describes the cooperation of the proposed dynamical wavelength allocation (DWA) with the PFEBA scheme to improve system performance. 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* λ_i *is available for transmission after time t, where* $i = 1, 2, \ldots, w$*, and w is the number of wavelengths.*
2) *RTT: Round trip times (RTTs) between the OLT and the ONUs, where* $RTT[i]$ *represents the round trip time between the OLT and the ith ONU.*

The PFWBA considers the unstable degree list, which is described in detail in Section 4.A, 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, 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 PFWBA then allocates the wavelength for each ONU group by group. The detailed process is described as follows.

1. Schedule the PFWBA from *Group*1 to *Group*3 according to the unstable degree list.

2. Select the requested frame in the same *Group* with the minimum transmission time, and schedule its transmission.

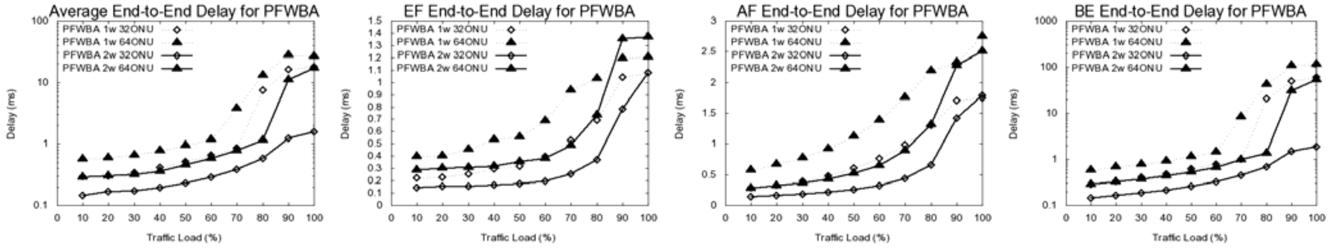
$$transmission\ time = RTT[i] + g + transmission\ timeslots$$

, where g is the guard time, and the transmission timeslots are obtained from the PFEBA.

3. Choose the earliest available wavelength transmission time $CAT[i]$.

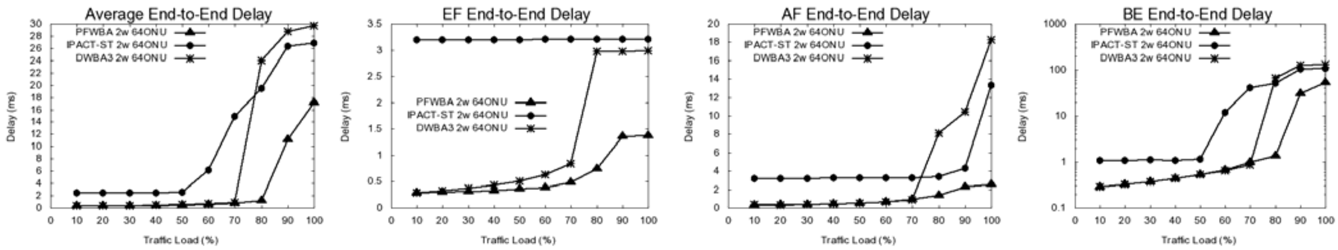
4. Update the $CAT[i]$ as $CAT[i] = transmission\ time + CAT[i]$.

5. Repeat the above operation until the requested frames in the same *Group* are scheduled, and schedule the requested frames in the following *Group*.



(a) (b) (c) (d)

Fig. 6 End-to-end delay for PFWBA (a) Average (b) EF (c) AF (d) BE



(a) (b) (c) (d)

Fig. 7 Compare end-to-end delay with other methodologies (a) Average (b) EF (c) AF (d) BE

V. Performance Analysis

The performance of the proposed PFWBA was compared with that of the DWBA3 [8] and WDM IPACT-ST [16] in terms of end-to-end delay, jitter performance and throughput. The results were examined by the OPNET simulation tool in infinite buffer situation. Two wavelength channels were adopted, and the downstream and upstream transmission rates were both 1Gb/s. The distance from one ONU to the OLT was assumed to be 10-20km, and the service policy was first-in first-out (FIFO). 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) [23]. 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 (e.g., voice applications) was modeled by a Poisson distribution, and the packet size was fixed to 70 bytes [24]. The traffic profile was as follows: 20% of the total generated traffic was considered as ET traffic, and the remaining 80% was equally distributed between AF and BE traffic [25].

A. *End-to-end delay*

Figure 6 compares the average end-to-end packet delay of the PFWBA for EF, AF and BE traffics classes with different numbers of wavelengths and ONUs vs. traffic loads. Simulation results show that the average end-to-end packet delays for EF, AF and BE traffics classes increased when the traffic load rose. Lowering the number of wavelengths and increasing the number of ONUs lengthened the end-to-end delay, as shown in Fig. 6. However, the EF traffics class in the PFWBA with two wavelengths and 64 ONUs had the longest packet delay when the traffic load exceeded 90%, as shown in Fig. 6(b). The possible reason is that the wavelength scheduling mechanism initially chose the wavelength with the first available time for transmitting the ONUs. The prior selection of wavelength for transmission may result in prediction inaccuracy. The ITU-T recommendation G.114 specifies the delay for voice traffic in access network at 1.5 *ms* [26]. Although the PFWBA scheme with two wavelengths and 64 ONUs had the longest delay, the EF end-to-end delay was still less than 1.5 *ms*.

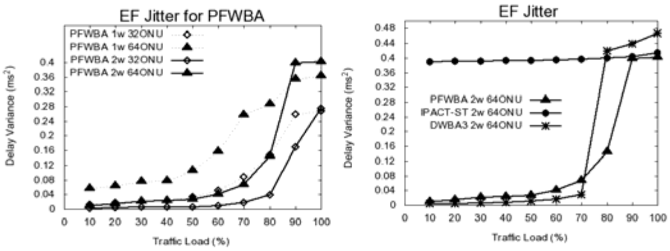
Figure 7 compares the average end-to-end packet delays among the PFWBA, DWBA3 and WDM IPACT-ST of all EF, AF and BE traffics classes with two channels and 64 ONUs for different traffic loads. Simulation results show that the proposed PFWBA outperformed the other two schemes for all traffic classes EF, AF and BE.

B. *Delay Variance Comparison*

Figure 8(a) compares the jitter performance of the PFWBA for EF traffic with different numbers of wavelengths and ONUs vs. traffic loads, respectively. The delay variance σ^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 delay time of EF packet i, and N is the total number of received EF packets.

Simulation results show that the delay variance for EF traffic lengthened when the traffic load rises. However, the PFWBA with two wavelengths and 64 ONUs had the highest delay variance when the traffic load exceeded 90%. The reason is that the number of ONUs with higher variance increased when the traffic load exceeded 90%, causing the unstable degree list to change continuously. Therefore, the wavelength scheduling mechanism and the upload sequence of ONUs also changed continuously.

The PFWBA with two wavelengths and 64 ONUs thus had the highest delay variance. Figure 8(b) compares the jitter performance of EF traffic among the PFWBA, DWBA3 and WDM IPACT-ST with two channels and 64 ONUs for different traffic loads. Simulation results show that the proposed PFWBA outperformed the other two schemes for the EF traffic class.



(a) (b)

Fig. 8 Delay Variance Comparison
(a) Jitter for PFWBA (b) Jitter Comparison

VI. Conclusion

The proposed protection architecture, CFT-WDM-EPON, enables feeder fibers to provide a recovery mechanism. If no failures occur in the PON system, then the CFT-WDM-EPON can share the loading of the working feeder fibers. When the failures occur on the OLT or feeder fibers, the backup fibers will recover the failed ones. Additionally, the 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. Although the PFWBA scheme with two wavelengths and 64 ONUs has the longest delay, the EF end-to-end delay is still lower than 1.5 *ms*, which is the recommended EF end-to-end delay in ITU-T Recommendation G.114.

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